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7/25/68

A COMPARATIVE STUDY OF THE EXHAUST EMISSIONS OF A WANKEL ENGINE USING GASOLINE AND NATURAL GAS AS FUELS

A THESIS

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William Stephen Bulpitt

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Master of Science in Mechanical Engineering

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A COMPARATIVE STUDY OF THE EXHAUST EMISSIONS OF A WANKEL ENGINE USING GASOLINE AND NATURAL GAS AS FUELS

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Chairman

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SUMMARY

The internal combustion engine has been shown to be one of the primary sources of air pollutants, especially unburned hydrocarbons, carbon monoxide, and oxides of nitrogen. Federal legislation has forced all manufacturers who anticipate future sales of automobiles in the United States to seek methods which will reduce the emissions of their cars by 90 per cent during the 1970-76 period.

In recent years the Wankel rotary engine has experienced a great deal of development and at the present time it shows promise as an alternative to the conventional reciprocating engine. Some sources believe that the Wankel is the solution to the automotive emissions problem, and while the evidence on this point is not yet conclusive, the Wankel does offer other definite advantages in weight, smoothness, and simplicity.

Much research has been done recently on finding alternative fuels for the internal combustion engine. Natural gas has been shown to be a low-pollution automotive fuel.

The main objective of this study was to design and construct an emissions laboratory suitable for measuring pollutants generated from a Wankel engine running on both gasoline and natural gas. The engine was run on these two fuels under similar operating conditions, varying the same parameters, to determine the production of unburned hydrocarbons, carbon monoxide, and nitric oxide.

The effects of varying the following parameters were investigated: engine rpm, load (manifold vacuum), ignition timing, and air-fuel ratio.

It was found that the use of natural gas as the fuel for a Wankel engine reduces exhaust emissions of the engine to levels below those produced using gasoline as the fuel by the following amounts: nitric oxide--55 per cent, unburned hydrocarbons--15 to 25 per cent, and carbon monoxide--50 to 60 per cent.

The emissions laboratory will be used for further tests. Attempts will be made to lower the emissions level of hydrocarbons further using natural gas, and further comparison studies of the engine with other power plants will be performed to determine the relative merits of the Wankel as a low pollution engine.

CHAPTER I

INTRODUCTION

The Problem of Automotive Air Pollutants

Since the early 1900's the internal combustion engine has been one of the most important mechanical systems used by man. It has enabled him to travel long distances over land and water and allowed him to conquer the skies. In terms of numbers, the manufacture of internal combustion engines has been most important to the automobile industry, and in the United States alone the number of automobile engines produced is approaching ten million units annually.

The American people have had a long and happy love affair with the automobile. From the outset, the car owner had a certain status; the rest of the world knew he had achieved some measure of success. At first the automobile was an absolute luxury, and then as the country became more mobile it became more and more of a necessity. Even today, however, the purchase of a new car is overshadowed in importance only by the purchase of a new house for most families.

Even through the 1950's and early 1960's the love affair with the automobile continued to blossom, accelerated by the horsepower race. Then suddenly things began to go sour, and the new car in the driveway seemed to lose some of its shine. Overnight the automobile was being blamed for darkening the skies with smog, causing new diseases, and killing thousands of innocent victims on the highways.

Of course, the automobile had been creating these problems all along, but only after urban areas became nearly overstocked with cars did people realize the impact cars were having on their environment. In the early 1950's the people of Los Angeles noted that their city was not as attractive a place to live as before the war. The air was not as clear as it used to be and sometimes it even smelled dirty. Cleaning up heavy industry and other pollutant sources failed to have a marked effect and finally scientists such as A. J. Haagen-Smit and others traced the roots of the problem to the automobile (1).*

The automobile has generally been recognized as a significant contributor of three air pollutants, and, to a lesser extent, the contributor of a fourth. The three most important pollutants are unburned hydrocarbons (hereafter referred to as HC), carbon monoxide (hereafter referred to as CO) and oxides of nitrogen (hereafter referred to collectively as NO_x). The fourth pollutant, of lesser significance, is particulate matter. According to figures released by the Federal government, the total air pollution emissions from all sources in the United States for the year 1968 was estimated at 214 million tons (2). Of this total it has been estimated that gasoline motor vehicles contribute 38.1 per cent, diesel motor vehicles 0.7 per cent and other transportation 3.5 per cent for a total contribution from transportation of 42.3 per cent or 90.5 million tons.

It can be concluded, then, that on a weight basis the motor

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*Numbers in parentheses refer to references in the Bibliography section.

vehicles on America's highways today account for about 40 per cent of the air pollutants occurring. It has been further estimated that the gasoline engine is responsible (on a weight basis) for 47.5 per cent of unburned hydrocarbons, 59 per cent of carbon monoxide, 32 per cent of nitrogen oxides, and 1.8 per cent of particulate matter each year (2). The particulate matter consists primarily of lead and, to a lesser extent, asbestos and rubber from brake linings and tires.

The figure of 40 per cent of pollution coming from automobiles may be misleading in some cases. For example, it has been estimated that 80 to 90 per cent of the pollutants generated in the Los Angeles basin are produced by the automobile, and in that area the problem is compounded by the geographic and meteorological conditions. The smog which occurs in Los Angeles has been analyzed as the final product of complex reactions between unburned hydrocarbons and oxides of nitrogen in the presence of bright sunlight. The health effects of this smog have been somewhat hard to assess, although eye irritation and decline of visibility have been obvious results. It is significant that probably because of these complex conditions, Californians have been concerned longest with the air pollution problem and acted earliest with legislation to curtail it.

In addition to smog formation, the automobile contributes CO to the air. It is a well-known fact that CO is absorbed more easily by the blood than is oxygen, and large enough doses can prove fatal. In addition, smaller doses over long periods of time can impair man's alertness and body functions (4).

Thus, it has been known for some time now that automobiles are bad for man's health, but it is only since about 1964 that the automobile industry, mostly under pressure from the federal government, has been taking steps to correct the problem. Various approaches have been attempted, ranging from modification of existing engines to entirely new concepts. The following sections will deal with these subjects.

The Wankel Engine and Its Development

The Wankel or rotary engine has been known to the automobile industry for some time now, having been invented by Felix Wankel in Germany in 1954. It, therefore, cannot really be considered a "new" concept, but only in very recent years have the engine's problems been sorted out to a point where mass production has been possible (5).

Basically the Wankel engine operates on the four-stroke or Otto cycle, like the majority of passenger car engines, but instead of pistons moving in a reciprocating motion the Wankel depends upon revolving rotors. Variable volume chambers are formed between the rotor, which is a curved-sided equilateral triangle, and the outer body which is a two-lobed epitrochoid (an epitrochoid is the shape generated by a point on the circumference of a circle rotating on a stationary inner circle).

In the original design the rotor was fixed and the outer casing rotated, but a Dr. Fröede of NSU (also in Germany) performed a kinematic inversion which resulted in a design allowing the outer casing to remain stationary with the rotor turning inside. This modification simplified the attachment of intake, exhaust, and other systems (5). NSU was

interested in developing the engine for use in automobiles, and by 1958 had developed a running engine. An exclusive license was sold that year to the Curtiss-Wright Corporation in the United States for development and marketing of an engine for the North American market. Since 1958 at least 21 additional licenses have been granted, most of them issued jointly by Wankel GmbH, the company holding the original patents, and by NSU, which holds the patents on Dr. Fröede's inversion. Most of the licenses dictate certain engine sizes and applications, as well as sales in certain geographic areas. Probably the license which has generated the most interest in the United States at this time is the non-exclusive license bought by General Motors in 1970 from Curtiss-Wright and NSU.

Presently NSU is selling cars (the Ro80) in the U. S. with Wankel engines, as is the Japanese company, Toyo Kogyo (the Mazda R100 and RX2). It is this last company with which this paper will be most concerned since a Mazda R100 engine was used for the experiments. This engine has been available in the U. S. since mid-1970 and has been in production in Japan since 1967. Development of the engine by the Japanese took some seven years.

A few words should be said about the operation of the engine. As previously mentioned, the engine operates on the Otto cycle and therefore has the same processes as a conventional engine. The engine cycle is shown in Figure 1. It should be noted that since the rotor is three sided, there are actually three separate cycles occurring simultaneously. Mechanically the engine is very simple and consists of three basic parts: the rotor, the eccentric shaft (same function as a crankshaft), and the outer housing.

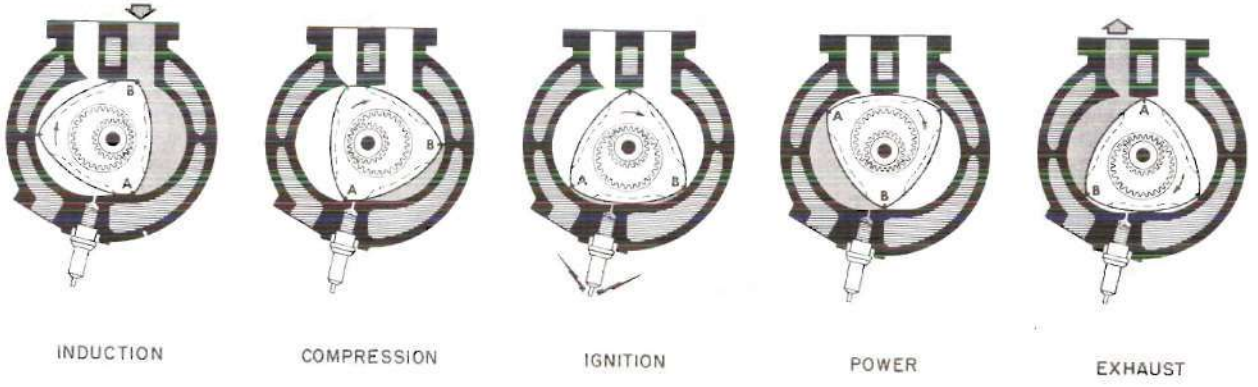


Figure 1. Wankel Engine Cycle.

The rotor revolves directly on the eccentric shaft, thereby doing away with connecting rods. Intake and exhaust timing are handled by ports (as in a two-stroke engine) so no valve gear is required. Orbital motion of the rotor is controlled by timing gears interior to the rotor and exterior to the eccentric shaft so that the rotor's gear "walks" around the smaller gear and maintains the timing.

Figure 1 shows the processes which occur in sequence in the engine. Figure 1(a) shows the rotor position during the intake portion of one side of the rotor, Figure 1(b) during the compression portion, Figure 1(c) during ignition, Figure 1(d) during the expansion cycle, and Figure 1(e) during exhaust. It should be noted that the rotor turns at 1/3 the speed of the eccentric shaft.

Although the simplicity of the engine is quite obvious, many problems have been encountered during its development. Sealing problems occurring at the rotor apexes have presented the greatest problem for developers of the engine. Seals must also be provided on the sides of the rotor for both combustion gases and oil since oil is usually circulated through the rotors as a coolant.

The octane requirement of the Wankel is less than that of a reciprocating engine of comparable performance. Engines currently available will perform well on leaded or unleaded gasoline of 90 octane or less. This low octane capability is due largely to the fact that the combustion chamber of the rotary engine has a higher ratio of surface area to chamber volume than a conventional engine. The trailing section of the combustion chamber is a wedge-shaped section (in general

practice) and this tends to quench the flame. Also the air-fuel charge is swept forward by the moving rotor at very high velocity producing a good deal of turbulence. These factors all contribute to the low requirements for octane number. For example, the Mazda R100 is advertised at 9.4/1 compression ratio but will run on 90 octane fuel. Conventional engines of this compression ratio would require premium.

Another area where problems have been encountered in the Wankel is overheating near the spark plugs. Since the combustion chamber does not have the benefit of cooling during the intake and compression strokes, the section of the chamber from the spark plug to the exhaust port is continuously heated. Sealing of the water jackets has been anticipated as a problem because of this continuous heating, and although Toyo Kogyo claims to have solved these problems some distortion problems have been encountered in the experimentation which will be discussed later (6).

At the present time the future of the Wankel as a passenger car engine is uncertain. It appears, however, that the Mazda automobile is selling and holding up quite well. The NSU Ro80 is being sold in small quantities in the U. S. after an absence because of emissions problems. General Motors is said to be working hard on Wankel engines at present and rumors are that the engine will be installed in 1975 full-sized cars and possibly in some 1974 compacts (7).

The primary advantages of the Wankel engine appear to be low weight, simplicity, and smooth operation. Some authorities believe that this engine will be a cure-all for exhaust emission control, but

in an uncontrolled engine this is certainly not the case. In fact, an uncontrolled Wankel engine puts out higher levels of HC than a recriprocating engine of comparable power, because the Wankel engine has a higher surface area to volume ratio in its combustion regions than a conventional engine. This higher ratio results in more cool areas which tend to quench the flame thereby producing unburned HC. This same phenomenon tends to help abate the formation of nitrogen oxides, however, since the peak temperatures and pressures in the combustion chamber tend to be lower. Nitrogen oxides have proved to be the hardest pollutant to control, and if the Wankel engine is really lower in NO_x, it may be the most expedient engine of the future (5,8).

Emission Standards and Current Methods of Abatement

An uncontrolled automobile engine has three major sources of air pollutants: fuel evaporation from tank and carburetor, crankcase blow-by, and exhaust emissions. California required all new cars to have positive crankcase ventilation (PCV) systems in 1963, and this requirement was nationwide in 1964. This standard does not allow pollutant gases to escape from the crankcase. Instead, the gases are reingested by the carburetor and burned.

Federal legislation required all cars to control evaporative emissions beginning with the 1970 model year. This was done by fitting vapor-tight systems on fuel tanks and carburetors so that hydrocarbons could not escape into the atmosphere.

The solutions to these first two problems were relatively easy, but the remedy for cleaning up exhaust emissions has been quite elusive.

California was the first state to establish exhaust emission standards for automobiles in 1968, and the rest of the nation soon followed suit. The responsibility for the establishment of standards and for the testing programs originally belonged to the National Air Pollution Control Administration (NAPCA) which became part of the Environmental Protection Agency (EPA) in late 1970.

Automobiles are tested for emissions on chassis dynamometers which simulate road load conditions. This procedure greatly simplifies the testing process since it is very difficult to install all the necessary instrumentation in the vehicle to be tested. The original test used was the "seven mode cycle" or "California Cycle" (because of its early use in that state) and it consisted of seven different operating conditions which when put together simulated an urban driving pattern (8).

Beginning in tests of 1968 cars, government tests were made using the "Federal Test Procedure" (FTP) which repeated the California Cycle nine times. Pollutant concentrations in the exhaust were analyzed continuously during the 16-minute test. The pollutant concentrations during each mode of operation were measured and multiplied by weighting factors to give pollution rates in grams per mile of vehicle travel. However, this test was not truly indicative of the mass emissions (8).

In 1972, another test was instigated using the constant volume sampling (CVS) procedure. The driving cycle used on the chassis dynamometer was a 23-minute, 7.5-mile, non-repetitive pattern called the LA-4 cycle. A constant fraction of the air-exhaust mixture was

collected in a bag, and concentration measurements at the end of the test were considered to give a true indication of mass emissions in grams/mile. In the cold start method of this test (CVS-C) the vehicle to be tested stands at constant temperature (70°F) for 12 hours before engine startup.

For 1975 and later, yet another procedure will be used called the CVS-CH test which is a combination of cold and hot start tests. Again the vehicle has a cold soak for 12 hours at 70°F. The driving cycle is the same 23-minute pattern used in the CVS-C. After the vehicle is run through the cycle, it is shut down for ten minutes and restarted. The first 505 seconds of the driving cycle are repeated. A constant fraction of the air exhaust mixture flow is collected: the first 505 seconds in a "cold transient bag"; the next 864 seconds in a "stabilized bag" and the repeat 505 seconds in a "hot transient bag." Emissions in cold and hot transient bags are weighted 0.43 to 0.57, respectively, and added to the emissions in the stabilized bag to give true mass emissions (8).

The most important legislation yet to affect automobile exhaust emissions are the 1970 amendments to the Clean Air Act. What these state, in effect, is that the 1975 automobiles must produce 90 per cent less CO and HC than the standards for 1970 automobiles, and that 1976 automobiles must produce 90 per cent less NO_x than 1971 automobiles. At this time it appears that the auto manufacturers are going to have a difficult time meeting these standards.

Table 1 gives a summary of the exhaust emission standards as set up by the Federal Government. It should be noted that there is not a slackening of the standards from 1971 to 1972, but the use of the CVS test rather than FTP gives higher pollutant indications.

Table 1. Federal Emission-Control Requirements for Light-Duty Vehicles

Model Year:	1968	1970	1971	1972	1973	1975	1976
Test Procedure:	FTP	FTP	FTP	CVS-C	CVS-C	CVS-CH	CVS-CH
			Emissions--gm/mi				
HC	3.4	2.2	2.2	3.4	3.4	0.41	0.41
CO	35.0	23.0	23.0	39.0	39.0	3.4	3.4
NO_x	NR	NR	NR	NR	3.0	3.0	0.4
Evaporation Losses gm/Test	NR	NR	6.0	2.0	2.0	2.0	2.0

NR--No Requirement.

In addition to the chassis dynamometer, a great deal of other expensive equipment is required to run a valid exhaust emissions test. The entire test procedures and requirements have been published in the Federal Registers of November 10, 1970 and July 2, 1971 (9,10). The National Academy of Sciences has said that the equipment required to carry out complete emissions tests costs about $100,000 (8). Thus, these setups will not likely be found in service stations or even state inspection stations anytime soon.

The minimum requirements for instrumentation include a flame ionization detector (FID) for hydrocarbons, a chemiluminescence analyzer for NO_2, and non-dispersive infrared (NDIR) instruments for CO and CO_2. In addition a CVS sampling system, chassis dynamometer and a great deal of support hardware is needed.

At this point it should be noted that the experiments performed for this thesis were not done according to the Federal test procedures. Instead, a hydraulic engine dynamometer was used, which lends itself better to research purposes. Additional equipment that was used consisted of an engine test stand, FID hydrocarbon instrument, and NDIR instruments for CO, CO_2, and NO. This equipment will be described more fully in a later section.

The tests that have been performed do not indicate compliance or non-compliance with federal standards. Furthermore the concept of the thesis makes this question irrelevant. The concept concerns a comparison of a particular engine operating under given conditions with two different fuels. In this case, relative pollutant levels are being sought.

At this point in time a good deal has been done by the automakers in working toward passage of the 1975 standards, but according to most industry spokesmen and the National Academy of Sciences as well, there is not much optimism towards meeting the 1975 standards with production line cars (8). Progress toward meeting the standards has been good in some respects, but misguided in others, as is shown in Figure 2.

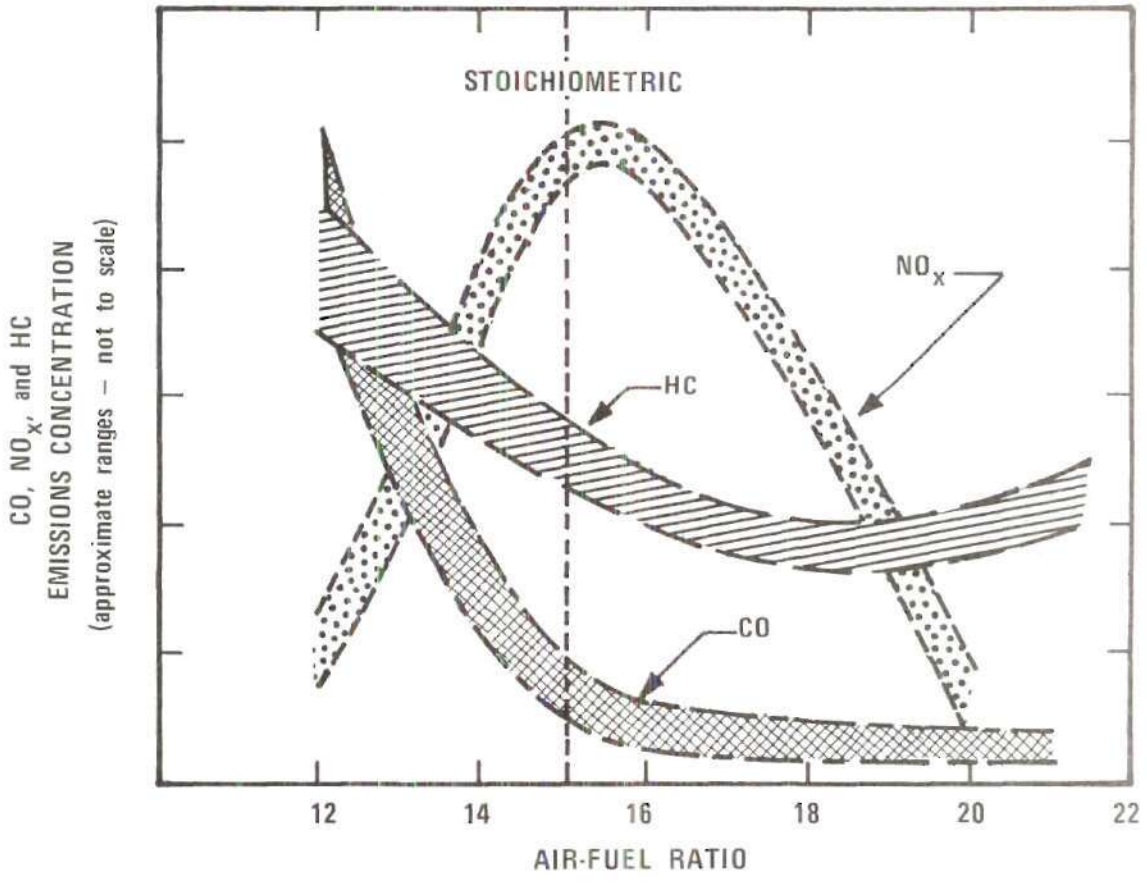


Figure 2. HC, CO, NO_x as Function of A/F.

As can be seen from the figure, the concentrations of the important pollutants are quite dependent on air-fuel ratio in the engine. This is true for Wankel engines as well as reciprocating engines. The major problem is that the air-fuel ratio which is best suited for reduction of HC and CO produces very high levels of NO_x. In addition, when adjustments are made to reduce NO_x, HC and CO go up. This trade-off is the largest problem the industry faces.

Initially, adjustments to engines were made with only the reduction of HC and CO in mind. Lean mixtures and retarded spark settings reduced these pollutants to acceptable levels, but the NO_x production was not curtailed and in most instances even increased (8). There are various methods that have been successfully used to control CO and HC, but NO_x remains the stubborn pollutant. At this point, the most feasible solution has been to recirculate 10-20 per cent of the exhaust gas into the carburetor. This inert gas acts as a heat sink and lowers combustion chamber temperatures which in turn lower NO_x production. NO is formed at high temperatures by the combination of N_2 and O_2 in the incoming air. The use of this exhaust gas recirculation or EGR, however, results in power and efficiency losses and impaired driveability of most cars.

To meet the 1975 and 1976 standards it will probably be necessary to use EGR but that in itself will not be enough. A rich mixture will also have to be used to further reduce NO_x, and high CO and HC will result. These can be reduced, however, by using a thermal reactor or catalytic reactor in the exhaust system. A secondary air supply will be needed to supply sufficient O_2.

A very helpful solution, which unfortunately has not yet been found, would be to find a catalyst that will reduce all three pollutants--NO_x, CO, HC. Of course, the major problem with catalysts is that they have to be replenished, and since the Federal Test Procedures call for 50,000-mile driveability tests, these may not prove to be practical.

Other approaches are being investigated, too, many of which deal with more accurate metering of the fuel, such as fuel injection. At present it is hard to say exactly how the engines of 1975 will look, but it is almost certain that they will cost more, have poorer performance, and achieve lower fuel economy.

Natural Gas as a Motor Fuel

There has been another approach to reducing exhaust emissions in use for some time: the utilization of alternative fuels, principally propane and natural gas. Propane has been used in trucks and fleet applications, and maintenance costs have been significantly reduced with this fuel since spark plugs last longer and the engines can be run for longer distances between oil changes (11). At present there is a fairly well organized distribution of propane in the U. S. since it is available at most truck stops.

Natural gas also has been in use as an automotive fuel for several years. Various approaches have been tried and the fuel can be stored as compressed natural gas (CNG) or liquid natural gas (LNG). The Georgia Tech School of Mechanical Engineering entered a car in the 1970 Clean Air Car Race (CACR) which was powered by natural gas and

gasoline in a dual fuel system. This system appears to be the best approach at this time since natural gas is not always readily available for refueling. The CACR car was basically a standard 1970 Ford with a six-cylinder engine and was equipped with a dual-fuel conversion kit, consisting of a venturi mixing valve air intake that enabled natural gas to be used. The special intake bolted right to the top of the standard carburetor and it was a simple matter to switch from one fuel to the other. Fuel was carried in three DOT-approved cylinders in the trunk of the car at about 2200 psi, giving the car a range of about 100 miles at interstate speeds. Refueling was accomplished with a truck-mounted tank supply and high pressure compressor.

The successive event to the Clean Air Car Race is the Urban Vehicle Design Competition (UVDC) to be held in August, 1972. Georgia Tech is again planning a natural gas powered entry, and the engine to be used is the subject of this thesis.

Several papers have been written demonstrating the fact that natural gas will reduce exhaust emissions, particularly CO and NO_x (11, 12). Natural gas has an octane number of about 130, thereby allowing engines to be operated at very lean mixtures and retarded spark.

Carbon Monoxide is reduced in auto engines burning natural gas largely because of the characteristics of the special mixing valve. The variable venturi provides uniform mixture distribution and maintains a constant air-fuel ratio mixture (12).

In conventional reciprocating engines, substantial reductions in hydrocarbons have been observed, but these reductions become much more

dramatic if the reactivity of methane (which is the primary constituent of natural gas) is taken into consideration. Most of the unburned hydrocarbons found in the exhaust of a natural gas powered engine are methane, and methane has been shown to have very little reactivity in the formation of photochemical smog (12,13). Also it should be noted that evaporative emissions should be nearly zero from a dual fuel system car or a car running solely on natural gas, since the carburetor will be dry and no hydrocarbons can escape.

Reduction of NO_x emissions results primarily because of the ability of engines to run on very lean mixtures with natural gas.

In addition, certain minor pollutants are reduced using natural gas: for example, lead is totally eliminated. Soot and carbon deposits are also greatly reduced. This is evident in the sampling train to be described later.

One of the major drawbacks to the use of natural gas as a motor fuel is power loss. In the CACR vehicle this loss was enough to affect driveability. In general, a 15-20 per cent loss when changing from gasoline to natural gas can be expected, and this power loss is due to several factors. The fuel enters the intake manifold as a gas, rather than as liquid droplets of gasoline, and occupies about 10 per cent of the available volume. This reduction in air capacity results in a power loss of about 10 per cent. In addition, the slower flame speed of a natural gas lowers peak cylinder pressures and further reduces maximum horsepower (12). If the engine has enough power to spare on gasoline, a 15 per cent reduction of peak power should be easy enough

to live with. The Mazda engine to be used in the UVDC car should still have plenty of power after the losses due to the use of natural gas.

It may be noted that some of the power loss can be recovered by raising the engine compression ratio, since the high octane rating of natural gas will allow this to be done without engine knock. This can be done in a conventional engine simply by milling the cylinder head, but it can be seen that it would be much more difficult to raise the compression ratio of a Wankel engine.

At present the major factor affecting the widespread use of natural gas as a motor fuel is availability. Natural gas reserves probably could not handle the conversion of all U. S. cars to natural gas, and of course there are few public service stations offering natural gas refueling. For fleet operation the fuel is quite feasible, however, especially when daily use does not exceed 80-100 miles. Several large fleets around the country have been converted to natural gas, and it has proven to be economical (12).

Another area where natural gas looks very promising as a motor fuel is for stationary engines. It has long been used to drive large gas engines in pumping stations, power generators, etc. Small Wankel engines powered by natural gas could perform very well as prime movers for generators, pumps, and refrigeration units. Vibration, noise, and maintenance costs would be reduced.

Thus, natural gas has been experimented with as a motor fuel in many applications. As stated previously, this thesis is concerned with a comparative study of a Wankel engine running on gasoline and on

natural gas, and the sections which follow will describe the equipment used and the experiments that were carried out.

CHAPTER II

DESCRIPTION OF APPARATUS

Laboratory Concept

Since the entry of a car sponsored by the School of Mechanical Engineering in the Clean Air Car Race, there has been considerable interest in establishing a laboratory which would allow measurement of exhaust emissions of internal combustion engines running under a variety of test conditions. There were various engines running on test stands in the laboratories for use by undergraduates, but none were late model engines or engines with exhaust emission controls.

Therefore, it was decided that a laboratory should be designed and constructed that would employ the latest emissions monitoring equipment and provide facilities for running at least two engines. A chassis dynamometer for running Federal test procedures was also desirable, but funds were not available.

Several engines were considered and it was decided that one engine should be a Wankel and the other should be a conventional engine of up-to-date design. Efforts to obtain a Wankel engine were begun and several problems were encountered. The only Wankel-powered cars for sale in the U. S. at the time were the NSU Ro80 and the Mazda R100. The NSU was a high-priced automobile and was not even considered. It was soon discovered that procuring a Mazda engine would not be easy since they were not available as separate units at that time. In fact, it

looked as though the only way to obtain an engine would be to buy the $2500 car and pull the engine out. This was done, with the help of the Atlanta Gas Light Company who provided the automobile.

The other laboratory engine obtained was a four-cylinder overhead cam Chevrolet Vega engine donated to the school by the General Motors Corporation.

Once the engines were obtained, the actual work of setting up the test stands was begun. This turned out to be a good deal more work than was originally anticipated. The engines were set up side by side with a common control panel between them. Each engine was connected to a hydraulic dynamometer which provided loading and measured power output. In addition, a complete exhaust gas sampling train was constructed for connection to either engine. More detailed descriptions of these components will be given in a later section. Each engine was equipped with a dual fuel capability for running on natural gas or gasoline.

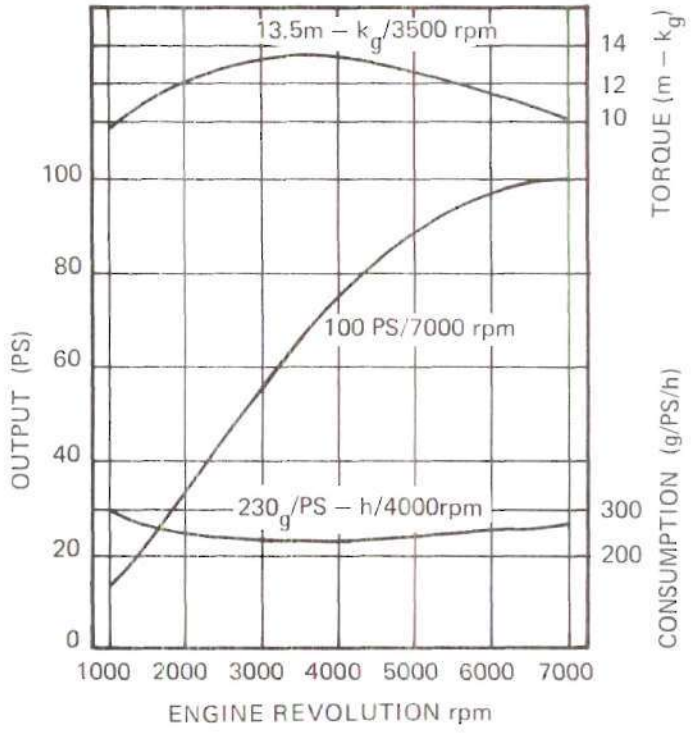
The original problem for this thesis was to be a comparison study of the exhaust emissions of the two engines running on gasoline. The problem was changed, however, to a comparative study of the Wankel engine running on gasoline and natural gas. This was considered the best course of action since the Wankel engine was slated for reinstallation in the Mazda body for entry in the Urban Vehicle Design Competition, and experience in running the engine with natural gas fuel was needed.

Wankel Test Setup

The engine used for these experiments was a Toyo Kogyo 10A engine as installed in the Mazda R100 automobile. It was a twin rotor Wankel rated at 110 SAE horsepower at 7000 rpm. The specifications, horsepower and torque curves are shown in Figure 3. Before installation in the test stand, the engine was weighed (less the thermal reactor but with all engine accessories and no transmission) at 257 pounds.

A special engine stand was fabricated from steel I-beams and mounted solidly to the cement floor of the laboratory. The dynamometer and engine were mounted solidly to this stand, and provision was made in the engine mounts for small position adjustments. The overall engine installation is shown in Figure 4.

The dynamometer used was a Taylor hydraulic dynamometer (or dyno), Model D-21, with a 6500 rpm maximum operational speed and a dynamometer constant of 6000. A Fairbanks-Morse 200-pound capacity beam scale was fitted to the dynamometer for accurate torque and horsepower readings. The dynamometer was coupled to the engine directly (no clutch or transmission was used) with a specially-made driveshaft containing two heavy-duty, automotive-type universal joints. Water supply to the dynamometer was directly from the building supply through a flexible rubber hose so that torque readings would not be affected. Exhaust water was dumped outside the building through a low restriction 2 1/2 inch pipe.



ENGINE (General Data)	
Type	Rotary piston engine, in line 2 rotor, water cooled
Displacement	491 cc x 2 rotors (29.96 cu. in x 2 rotors)
Compression ratio	9.4: 1
Compression pressure	6.0 kg/cm^2 at 280 rpm (85 lb/in^2 at 280 rpm)
Max. brake horsepower	100 PS/7,000 rpm (JIS) 110 HP/7,000 rpm (SAE)
Max. torque	13.5 m-kg/3,500 rpm (JIS) 100 ft-lb/4,000 rpm (SAE)
Port timing:	
Intake opens	Primary: 32° A. T. D. C. Secondary: 32° A. T. D. C.
Intake closes	Primary: 40° A. B. D. C. Secondary: 40° A. B. D. C.
Exhaust opens	75° B. B. D. C.
Exhaust closes	35° A. T. D. C.

Figure 3. Mazda Engine Specifications.

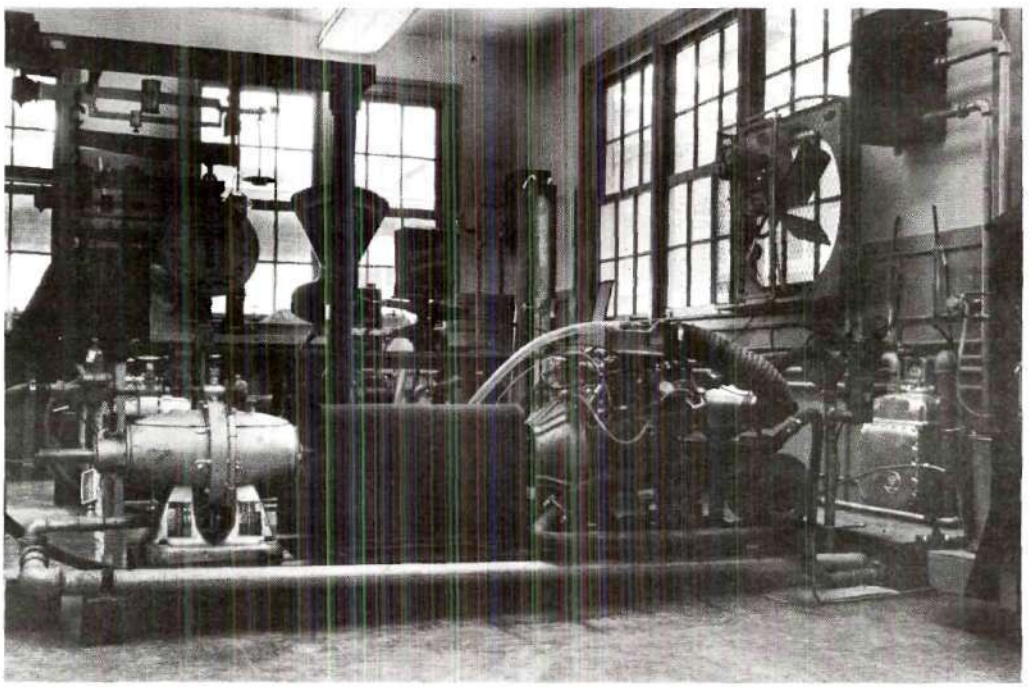


Figure 4. Mazda Engine Test Setup.

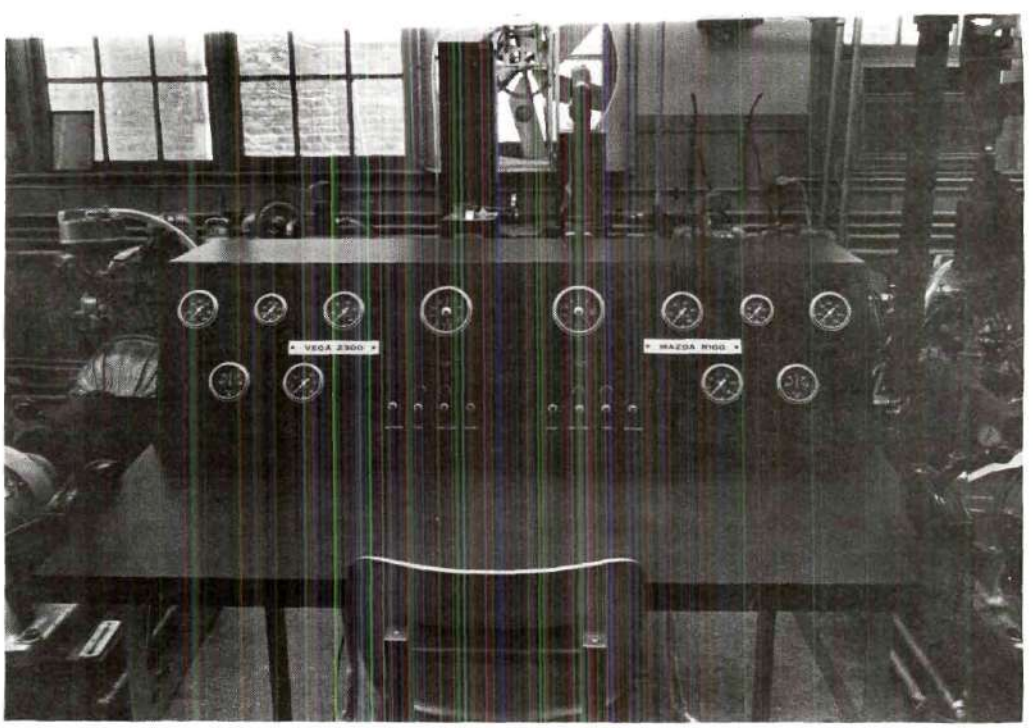


Figure 5. Engine Control Panel.

Operational instrumentation was housed for the Mazda and Vega engines together in a specially-built control panel as shown in Figure 5. Instruments used were all of Stewart-Warner manufacture and included 0-8000 rpm Model 970 tachometer, oil pressure 0-100 psi, oil temperature 270°F, water temperature 250°F, amperes, vacuum gauge 0-30 inches Hg, and a 10,000 hour hourmeter. Throttle control was accomplished with a marine-type throttle as shown in the figure. The engine was cooled using two separate cooling systems. In the Mazda engine oil is circulated through the rotors to help cool them, as shown in Figure 6. This necessitates a rather large capacity oil cooler in the car and this was retained in the dyno setup. A squirrel cage fan was used to blow air through the oil cooler.

The water circulating system posed some problems, and the system which was used never proved to be entirely satisfactory, and may have been largely responsible for the failure of certain engine components during the test program. (This will be discussed more fully later.) The engine water was circulated through pipes and into a holding tank of approximately eight gallons capacity. When the water being circulated exceeded a predetermined temperature (usually 180°F under most test conditions) a thermostat in the outflow pipe opened a solenoid valve and exhausted the hot water. When the holding tank level dropped sufficiently, a make-up float valve would add fresh cool water to the system. Under most conditions the system performed satisfactorily but occasionally there were overheating problems.

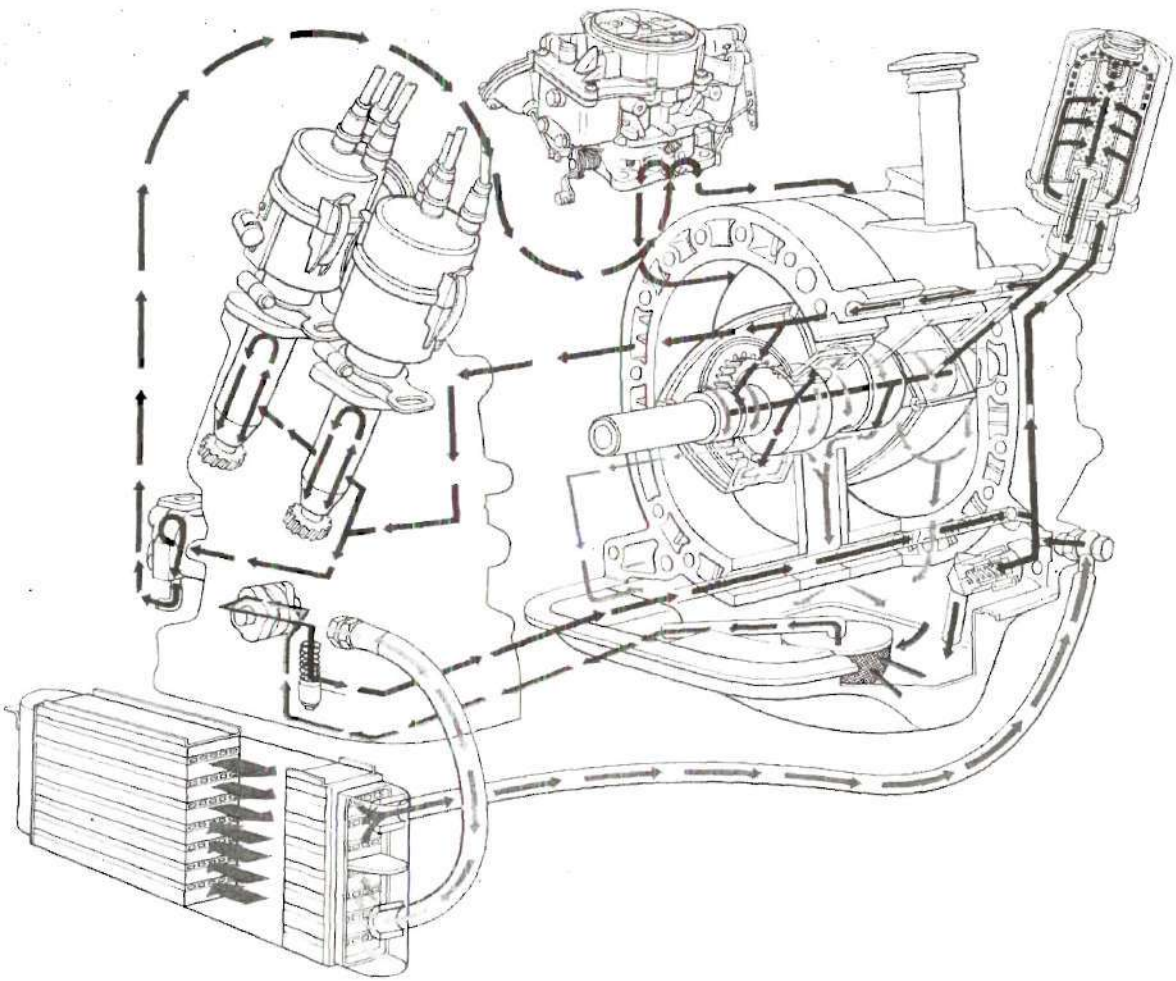


Figure 6. Mazda Lubrication System.

Gasoline was supplied to the engine from a small two-gallon can, which could be easily weighed, through the standard Mazda electric fuel pump to the stock four-barrel carburetor. This provided enough gasoline for several tests before refilling was necessary.

Natural gas was supplied through an alternate arrangement. Gas entered the building from the gas main and was passed through a dry gas meter, an electric solenoid valve (controlled from the engine control panel), and a regulator, before entering the natural gas mixer. The mixer was a Model 300A from the Impco Manufacturing Company. An adapter plate was made for the Mazda Carburetor, and operation was like any other dual fuel system. The mixer was equipped with a bypass arrangement that could be opened for gasoline operation with less restriction. This was always done when the engine was being run on gasoline.

Engine exhaust was routed out of the building and through a low restriction truck muffler. The system was well sealed and the laboratory was well ventilated with a large exhaust fan so fumes were never a problem.

Several further points should be noted about the engine. It is quite obvious that a great amount of development time went into this powerplant, and especially noteworthy is the sophistication of the air pollution control system. It must be noted here that not all of the emission control hardware was used when the experiments were performed, but the systems that are provided with the car are worthy of mention. Figure 7 gives a wiring diagram for the emission controls and related equipment as it was set up on the test stand.

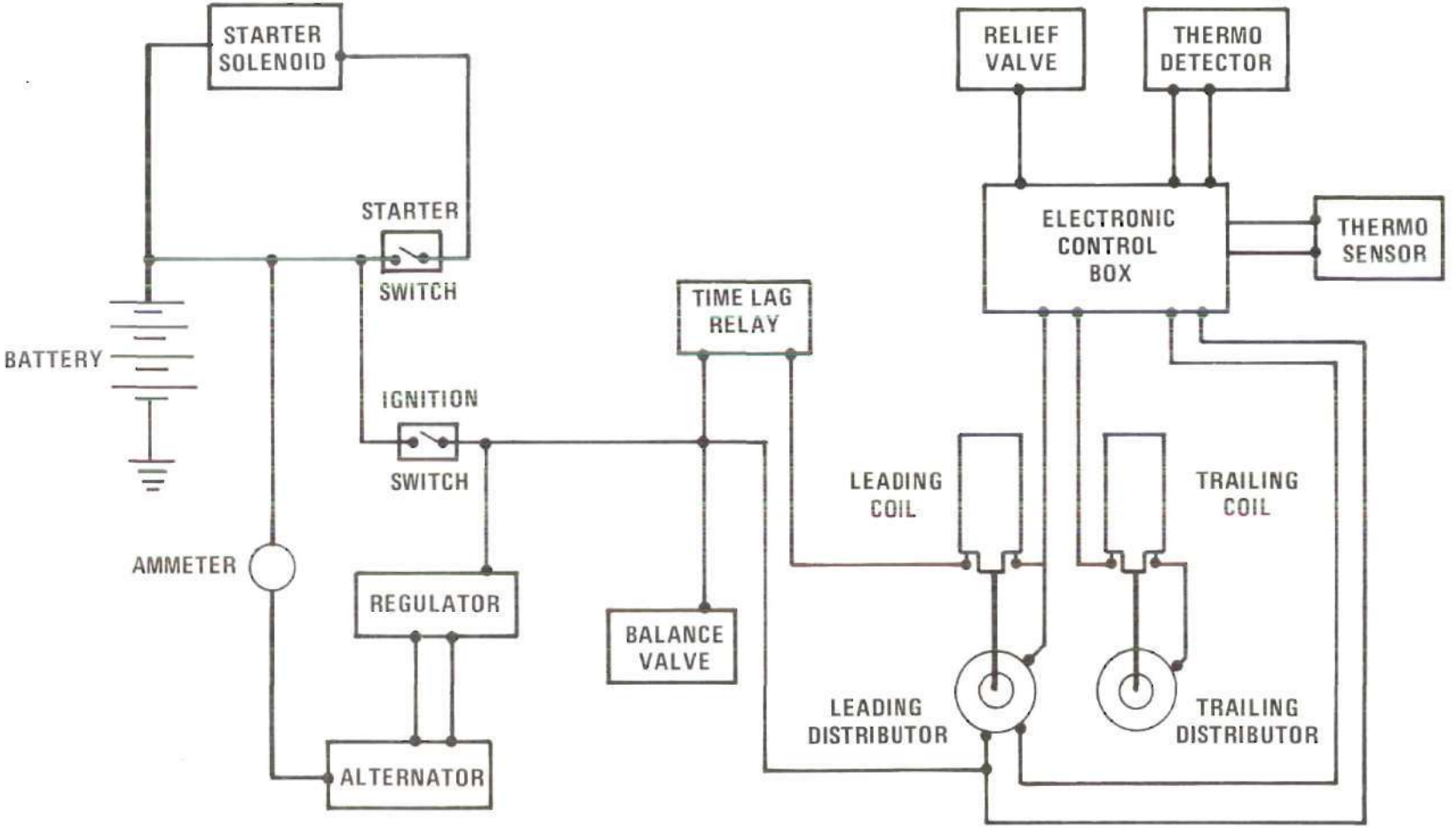


Figure 7. Emission Control Wiring Diagram.

The Mazda R100 as equipped from the factory has three basic air pollution control systems, which together allow it to meet the U. S. emissions standards. The engine has an air injection system (with air flow control system and ignition control system), a positive crank case ventilation system, and an evaporative emission control system (14).

The Mazda engine's thermal reactor is designed to oxidize excess CO and HC emissions before passage out of the car's tailpipe. Secondary air is injected by an air pump (run by a fan belt from the eccentric shaft) through air injection nozzles into the two exhaust ports of the engine. Exhaust gases and secondary air then pass into a cast thermal reactor where the actual afterburning process takes place.

The R100 engine is equipped with two distributors, and the fuel is ignited by two spark plugs in each rotor chamber. The "leading" spark plugs fire when the rotors are at top dead center of their cycle, and the trailing spark plugs fire at 10° after top dead center (at idle with no vacuum advance). The air flow control system and ignition control system control the flow of secondary air and the firing of the trailing spark plug, respectively. The overall emission control system consists of the air pump, check valve, coasting valve, air supply valve, balance valve, time lag relay, thermosensor, vacuum switch, electronic control box, air injection nozzle, thermal reactor, and hoses necessary to connect these components.

The air pump used in the air injection system is a vane-type pump and provides air at about 1 psi at 900 rpm and 2.5 psi at 2500 rpm. The air pump inlet is connected to the air cleaner and the outlet

is connected to the relief valve and the check valve. The check valve prevents exhaust gas from flowing back into the air pump in the event of a backfire or in the event of a drive belt failure.

The relief valve performs two functions. It releases excessive secondary air when the pressure developed by the air pump is greater than 2.4 psi. Another valve called the positive relief valve is operated by the manifold vacuum. The positive relief valve is controlled by an electrical solenoid which keeps the vacuum line to the valve open normally. When the engine speed becomes high the control box causes the solenoid to close the vacuum sensing line (this can also occur when the "coasting" valve opens) and the relief valve is opened, dropping the secondary air pressure (14).

Two more valves which are part of the emission control system are the anti-afterburn valve and the coasting valve. These are provided to prevent rich mixtures from occurring when decelerating the engine or shifting gears (14). Without the coasting valve, under deceleration the air-fuel mixture becomes rich and CO and HC levels will rise accordingly. To avoid these conditions the anti-afterburn valve and the coasting valve maintain the air-fuel mixture at the proper ratio by opening a fresh air passage from the air cleaner to the intake manifold in accordance with the change of vacuum in the intake manifold.

An additional system consists of the air supply valve, balance valve, and time lag relay. This system is provided to reduce exhaust emissions which may occur if the engine is shut off while it is being raced and also to prevent the engine from "dieseling" after shutoff.

When the ignition switch is shut off the balance valve opens the vacuum line which leads to the air supply valve, thus opening the valve allowing fresh air from the air cleaner to enter the intake manifold to obtain the proper air-fuel mixture. The time lag relay allows the leading spark plug to fire for a fixed period of time immediately after the ignition switch has been cut off. This causes the remaining air-fuel charge (which has been controlled by the air supply valve and balance valve) to burn within the engine.

Two signals are provided to the control box to monitor engine temperature. The "thermosensor" detects the temperature of the engine coolant and acts in controlling the secondary air supply and the trailing spark plug. The "thermodetector" senses the underhood temperature (in the car) and sends a signal to the control box which also effects the actuation of the trailing spark plug.

An additional system is provided in the vacuum advance mechanism of the leading distributor. This is a vacuum switch which supplies additional information to the control box for the purpose of cutting the trailing ignition coil on or off.

The control box is the heart of the emissions control system and receives information about engine temperature, manifold vacuum, and engine rpm. When the control box is working properly, the trailing spark plug should be firing up to about 2000 rpm, it should not be firing between 2000 and 4000 rpm, and it should begin to fire again above 4000 rpm. This process is necessary for several reasons. At low engine speed the large surface area-to-volume ratio of the combustion

chamber causes a large quench area at the rear of the rotor side which increases HC emissions. Therefore, another spark plug is fired to help keep the air-fuel charge in this area burning. As engine speed builds up, temperatures increase and the time during which quenching can take place decreases. Thus the trailing plug is no longer necessary. The trailing plug is reactivated at higher rpm, however, because it has been found to help power output (6).

It should be noted here that in the interest of simplifying the comparison tests of this engine running on different fuels, the air pump and the thermal reactor were removed, and a specially-built exhaust manifold was fitted in place of the thermal reactor. Also, it was discovered that the thermosensor was apparently not operating correctly and as a result the trailing spark plug was not shutting off between 2000 and 4000 rpm. Therefore, the tests that were run were made with both plugs firing at all times.

Another note should be made about the engine's lubrication. A metering pump is fitted and provides a small amount of oil that drips into the gasoline in the two float bowls of the carburetor (see Figure 6). This oil mixes with the gasoline and is burned with the air-fuel charge in the engine. This is supposedly done to help lubricate the apex and side seals of the rotor (6,15). Of course, the use of this arrangement is not possible with natural gas since the fuel does not enter the carburetor. It appeared that lubrication was going to be a problem. Much thought was given to this problem and the conclusion was that the main purpose in trying to lubricate the seals is to reduce

friction due to carbon deposits on the rotor, seals, and housings. The amount of oil injected in this manner is small, about 5.5 cubic centimeters in 10 minutes at 2000 rpm (15). Therefore it was decided that in natural gas operation the oil from the metering pump would be allowed to drip into the dry float bowls where some of it would be drawn into the engine through the main carburetor jets. It was verified that the oil was actually being drawn into the engine by dismantling the carburetor after running the engine on natural gas. There was no appreciable buildup of oil in the float bowls.

Further discussion of the engine will be found in a later section. It was quite apparent in working with the engine that it was well engineered and great amounts of time had been spent on details. Before removal of the engine from the car it was driven for about 1200 miles by the author and many others, and all were impressed by engine response and smoothness, and the car's brisk acceleration.

Emissions Instrumentation and Sampling Train

Measuring air pollutants contained in the exhaust of an automobile is a difficult process, and in setting up the emissions laboratory for thesis experiments, many unforeseen problems were encountered.

The initial idea was to construct a sampling train which would measure all the pollutants dealt with in the Federal test procedures. Funds were not available to set up a complete laboratory to actually run the Federal test procedures, but the equipment that was obtained could eventually be used in such a system. Additional equipment needed for this capability is a chassis dynamometer, a constant volume sampler

(CVS), and a chemiluminescence instrument for measuring NO_2.

The laboratory was set up with the following instruments integrated into a sampling train: a flame ionization detector (FID) for measuring total hydrocarbons, and non-dispersive infrared (NDIR) instruments for measuring NO, CO_2, HC, and CO. A diagram of the sampling train is shown in Figure 8 and a photograph of the equipment is shown in Figure 9. The emissions instruments will now be discussed separately.

Hydrocarbons (FID)

Principal measurement of hydrocarbons was made with a Beckman No. 400 Hydrocarbon Analyzer. This analyzer works on the principle of ionization in a hydrogen flame. That is, the exhaust sample is passed through a hydrogen flame which is monitored for electrical conductivity. The conductivity of the flame will vary according to the concentration of hydrocarbons present in the sample. The analyzer used was equipped with several options including automatic fuel shutoff and a mixed fuel accessory. The mixed fuel accessory provides better instrument performance when the sample may have variable oxygen content, as is true with automobile exhaust gases (17).

The fuel used for the hydrogen flame was a mixture of 40 per cent hydrogen and 60 per cent nitrogen, supplied to the instrument at 30 psig. Hydrocarbon-free air was also necessary for the hydrogen flame. Initially "zero-air" certified to be hydrocarbon free (less than 0.2 ppm HC) was used but it was discovered that a good grade of compressed air worked just as well for the sensitivity required (10 ppm).

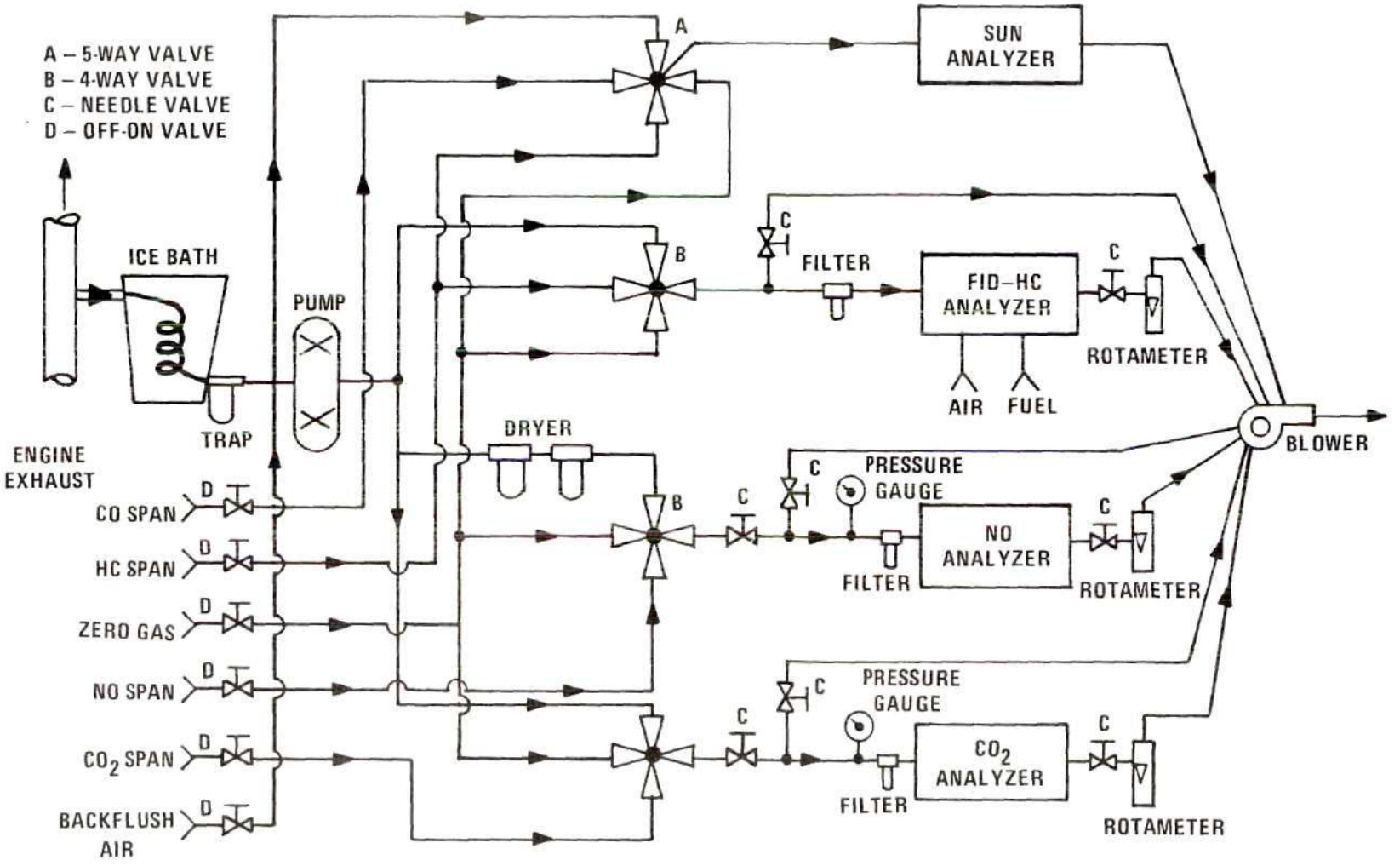


Figure 8. Diagram of Sampling Train.

Figure 9. Photograph of Sample System.

The air was supplied to the instrument at 7 psig. The instrument was equipped with internal pressure regulators for fuel, air, and sample pressure. Sample pressure will be discussed in a later section. The automatic fuel shutoff stopped fuel flow in the event the flame extinguished. Both fuel and air were stored in high-pressure cylinders equipped with pressure regulators.

Once in operation, the calibration of the instrument was quite easy. The zero point was set using the compressed air as zero gas, and the span point was set using a known concentration of propane, C_3H_8. Once a span point was set, the sample could be read out directly in ppm by volume. That is, if the span point is set arbitrarily on the dial, for example, 10 on the dial signifying 1000 ppm of propane, a reading due to a sample of 500 ppm propane would indicate 50 on the dial and could be read off directly as 500 ppm propane. Since most HC emissions measurements are recorded as ppm hexane, C_6H_X, the propane concentrations must be divided by two to give hexane equivalents. Thus, one span point is set and since instrument response is linear, the sample concentrations (higher or lower than the span point) can be read out directly. Calibration gas (propane) was also stored in a high-pressure cylinder and supplied to the instrument when necessary. The gas used for span calibration was a concentration of 970 ppm propane (or 485 ppm hexane). The supplier certified that the concentration of the gas was accurate to ±1 ppm. More will be said about instrument calibration later.

The sensitivity of the Beckman analyzer can be adjusted from 4 ppm CH_4 to 10 per cent CH_4 when using mixed fuel. On a carbon weight basis this means that, at worst, sensitivity would be accurate to less than 2 per cent hexane (17).

Nitric Oxide (NDIR)

Nitric oxide (NO) in the exhaust was measured using an Olson-Horiba AIA-2 non-dispersive infrared analyzer. The instrument had two ranges: 0-1000 ppm NO, and 0-4000 ppm NO. The principle of measurement is rather straightforward. Infrared light from identical sources is passed through two cells, one containing a reference gas and the other containing the sample gas. The infrared beams pass through an optical chopper and into a "gas microphone" detector. A portion of the infrared radiation passing through the sample cell is absorbed by the component of interest before it reaches the detector. The percentage of radiation absorbed is a function of the concentration of the component of interest in the sample. This percentage is read out on a meter. Again, a zero point and a span point must be set. The compressed air is used to set the zero, but the span point is set this time with a known concentration of NO in nitrogen. The accuracy of the NO concentration is certified by the supplier to be ±1 ppm. When the sample gas is passed through the analyzer, a reading is made on the meter. This reading can then be applied to the appropriate calibration curve, and the concentration of NO can be determined (18).

The manufacturer's stated accuracy of this instrument is ±1 per cent, and sensitivity is 0.5 per cent of full scale (18).

Carbon Dioxide (NDIR)

Carbon dioxide (CO_2) concentrations in the exhaust must be known to determine exhaust dilution. The instrument used to measure CO_2 was almost identical to the one used for NO. The analyzer section contained a different sample/reference cell, and the amplifier section provided only one range (0-15 per cent CO_2) but operation and calibration was virtually the same. Of course, a different calibration curve was supplied with this instrument, and the span point was set this time with a known concentration of CO_2 in nitrogen. Accuracy of the span gas was certified by the supplier to be ±.01 per cent. Accuracy and sensitivity specifications are the same as for the NO instrument.

Carbon Monoxide and Hydrocarbons (NDIR)

Carbon monoxide (CO) and additional hydrocarbon (HC) measurements were made with an exhaust emission tester manufactured by the Sun Electric Company. Its quality, accuracy, and sensitivity were not in the same class as the Beckman and Olson-Horiba instruments, but it offered simplicity and ease of calibration.

The Sun analyzer contains two Beckman NDIR analysis cells, one for hydrocarbons and one for carbon monoxide. The readout is on two large meters: hydrocarbons being in ppm hexane, and carbon monoxide in percentage. No calibration gases are required, but internal calibration is provided, and involves an additional chopper for each infrared beam.

The Sun analyzer is not really suited to research with high accuracy since its accuracy is ±10 per cent of full scale, but it was all that was available to measure CO at the time.

FID hydrocarbon analyzers are said to give higher indications of concentrations than NDIR, and most sources say that NDIR concentrations can be multiplied by 1.8 to obtain FID concentrations (9,10). No correlation tests were done between the two for these experiments, since action of the Sun hydrocarbon meter was quite erratic during most of the testing program. The irregularity of the instrument has since been repaired. However, no HC readings will be recorded from the Sun instrument.

Once all the instruments were on hand, a sampling train had to be built to connect them into a system. As can be seen in Figure 9 on page 37, three of the instruments were installed in a specially-built cabinet and the Sun instrument was connected to this. Note that a third Olson-Horiba unit can be seen at the bottom of the figure. This is a CO analyzer but was not operational at the time these tests were made.

The overall concept of the sampling train is similar to systems that can be purchased as packages from manufacturers such as Olson-Horiba or Beckman. Another look at Figure 8 on page 36 will show the arrangement of the components. As can be seen from the figure, the sample is pulled out of the engine's exhaust through a stainless steel probe and through an ice bath. When the entire system is in operation, two pumps act to pull the sample: the Sun instrument has its own pump which has a capacity of up to 50 standard cubic feet per hour (SCFH) and the rest of the instruments are supplied by a Model MB-110-10 welded bellows vacuum pump/compressor manufactured by the Metal Bellows

Corporation. This pump can supply up to 66 SCFH of air, but was usually called upon for considerably less.

The ice bath consisted of a coil of 3/8" O.D. stainless steel tubing mounted in a large stainless steel bucket. Cracked ice was placed in the bucket each time the sampling train was to be used. Thus the incoming exhaust sample was cooled and most of the water was condensed out. This was necessary since excessive water in the sample might damage the instruments and affect the readings (particularly of the NO instrument). Condensed water was collected in a small trap downstream of the condenser. A cleanable filter was located in the trap as well. During operation of the system the trap had to be emptied periodically.

A great deal of tubing was necessary to construct the sampling train. As a general practice, the instrument manufacturers recommend the use of stainless steel or teflon tubing for use in contact with exhaust gases, and this was done as far as possible, except in certain instances where copper tubing was substituted. Almost all tubing connections were made with Swagelok fittings (made by the Crawford Fitting Company). These ensured leak-free connections which could withstand repeated connection and disconnection. All off-on, needle, and five-way valves used in the sampling train were stainless steel Whitey valves, which came equipped with Swagelok connections.

After the sample was passed through the ice bath, a portion was pulled off by the Sun tester. This portion passed through a five-way valve as shown in the figure and on to the tester where the sample was

analyzed for CO and HC. The five-way valve provided calibration of the instrument with hydrocarbon span, carbon monoxide span, and zero gases, but since the instrument was equipped with internal calibration these were rarely used, and then only for comparative purposes. The Sun instrument had an additional filter and water trap in its input line for use when testing engines in automobiles. In operation with the sampling train this trap accumulated no water, however, due to the effectiveness of the ice bath.

The remainder of the exhaust sample (minus the portion routed to the Sun tester) passed through the Metal Bellows pump and was split up among the hydrocarbon, carbon dioxide, and nitric oxide analyzers.

The portion of the sample destined for the hydrocarbon analyzer passed through a Wilkerson 1049 filter (which removed particles greater than three microns in size) and into the analyzer. Some of the sample was usually bypassed around the analyzer and out the exhaust. The portion which passed through the analyzer then flowed through a Brooks 2-18 SCFH rotameter (which allowed flow rate to be set) and out the exhaust. A four-way valve was provided upstream of the analyzer so that hydrocarbon span gas, zero gas, or the sample gas could be routed to the instrument.

The portion of the sample bound for the nitric oxide analyzer passed first through a drying apparatus which consisted of two Wilkerson 4001-2 dryers containing indicating silica gel. These removed any moisture that may have remained in the sample after passing through the ice bath. The silica gel initially had a blue color which turned

red as moisture was absorbed. The silica gel was regenerated by heating in a vacuum oven. Originally these dryers were directly downstream of the ice bath but the silica gel absorbed hydrocarbons and affected the readings of the hydrocarbon analyzer, so the dryers were finally placed only in the NO circuit. According to information from instrument manufacturers it was decided that it was only necessary to take these extra drying steps in the case of the NO analyzer.

After passing through the dryers the exhaust sample passed through another Wilkerson 1049 filter and into the NO analyzer. After passage through the analyzer the sample flowed through another Brooks 2-18 SCFH rotameter and on to the exhaust. Another four-way valve was provided upstream of the analyzer for routing NO span gas, zero gas, or sample gas to the analyzer. In addition, a needle valve was provided upstream of the four-way valve for throttling of the sample when necessary, and another needle valve was provided for bypass around the analyzer. Sample pressure was monitored at the entrance to the NO analysis cell with a Magnehelic gauge registering 0-10" W.G.

The portion of the sample routed to the CO_2 analyzer was subjected to almost identical treatment as that for the NO analyzer, except that the sample was not dried with silica gel. A Wilkerson filter was provided just upstream of the analyzer, and sample pressure was monitored at the entrance to the CO_2 analysis cell with a 0-8" W.G. Magnehelic gauge. After passing through the CO_2 analyzer the sample flowed through another 2-18 SCFH Brooks rotameter. Valves provided for the CO_2 analyzer were identical to the NO. A four-way valve upstream of the

analyzer routed CO_2 span gas, zero gas, or sample gas to the analyzer, while a needle valve downstream of the four-way valve was provided for sample throttling, and another needle valve was provided for bypass around the analyzer.

The exhaust from the three analyzers in the cabinet and their bypass valves was routed to a common manifold. This manifold supplied the exhaust gases to a squirrel cage blower which blew them out of the laboratory. Likewise the exhaust from the Sun instrument was routed outside the building.

Off-on valves were provided on the control panel for all span and zero gases, which were stored in high pressure cylinders adjacent to the sampling train. Each cylinder in use was equipped with a single-stage pressure regulator and was connected to the sampling train through teflon or stainless steel tubing. A system backflush with compressed air was also provided.

Once the whole system was constructed several problem areas were found. As mentioned previously, the drying apparatus absorbed hydrocarbons and had to be repositioned. The Beckman analyzer had been equipped with its own sample pump which failed after a very short time, so the single bellows pump was used alone. The Beckman instrument was shipped with a defective sample pressure gauge which caused some difficulty but this was soon replaced. Also the flame would not light initially and some juggling had to be done with air and fuel pressures until a satisfactory operating point could be found.

Some difficulties were also encountered with the Olson-Horiba analyzers. The NO analyzer would not calibrate as demonstrated in the instruction manual and adjustments had to be made to the infrared chopper. The CO_2 analyzer would not calibrate at all and was eventually sent back to the manufacturer. When it was returned, provision was made for measuring sample pressures with the Magnehelic gauges on the Olson-Horiba instruments and both the NO and CO_2 instruments operated satisfactorily.

The final instrumentation was provided for measuring air-fuel ratios of the engine. As noted previously a dry gas meter was provided by the gas company for measuring natural gas volumes. Readings were made from it in cubic feet of gas at standard conditions, which are 60°F and 8" W.G. inlet pressure to the meter. Small U-tube water manometers were attached to measure inlet pressure and outlet pressure downstream of the pressure regulator.

Air flows were measured to the engine using a Meriam 200 CFM capacity laminar flow element, coupled with a Meriam 20" vertical water manometer. The laminar flow element provides a pressure differential across a fine honeycomb matrix which varies linearly with air flow. A calibration curve is provided and once the pressure differential is known, the air flow in SCFM can be found. The pressure differential could be measured to the nearest .001 inches of water with the manometer.

Gasoline flow was measured using a very simple method. The fuel supply for the engine was contained in a two-gallon can resting on a weighing scale. The scale could measure 0.01 pound, and fuel flow was

measured simply by calculating the change in weight of the can in a given length of time, as measured with a stopwatch. Thus, with accurate air flow and fuel flow measurements, air-fuel ratios could be easily determined.

As has been discussed, many problems were encountered in setting up all the apparatus for this project, but once all the details were worked out the overall system performed quite well, and data points could be run quickly by one person.

CHAPTER III

EXPERIMENTAL PROCEDURE

Original Plan for Experiments

When construction of the emissions laboratory had been completed and all the instruments were working properly, a decision had to be made as to what the investigation should include and what tests should be run. As mentioned before, the original plan was to compare the Vega engine with the Mazda engine (both running on gasoline) to see what advantages or disadvantages a Wankel engine might have over an up-to-date piston engine from an exhaust emissions viewpoint. This idea was discarded in favor of an investigation involving only the Wankel engine, mainly because it seemed to be a more interesting project and also because some data from the engine running on natural gas would prove useful for later work.

Thus, it was decided to plan a testing program that would demonstrate the effects of varying different engine parameters on the exhaust emissions. This program would be run completely using natural gas as a fuel, and again using gasoline as a fuel.

Parameters to be Studied

It was soon discovered that an engine-testing program could quickly become overambitious in its scope. Very small incremental variations of all the parameters affecting the operation of an internal

combustion engine can quickly generate thousands and thousands of data points, but many will be meaningless and will only serve to draw unimportant conclusions. Several false starts were thus made in the data-taking process before a final test program was arrived at which would yield some meaningful results. For example, originally some data were taken running the engine in 500 rpm increments, for set conditions of air-fuel ratio, spark advance and dynamometer load. However, with an engine that has a 7000 rpm redline, this would involve 13 points. Considering the fact that it took about 15 minutes to run each data point, the scope of the project looked far too great. As it was, with all the problems that developed in the laboratory equipment, time was very much a factor in the experiments.

RPM

The first parameter to be considered was engine speed, for this has often been demonstrated to have an important effect on exhaust emissions (3,11,12). As mentioned above, it was decided that 500 rpm steps would produce too much data, the trends of which could easily be seen with fewer points. Therefore, it was decided to run at least four rpm settings for fixed conditions of the other parameters. For each setting of the other parameters a run was made at no load (idle at 900 rpm) and then at engine speeds of 1500 rpm, 3000 rpm, 4500 rpm, and 6000 rpm. Before the engine was removed from the car some data were taken at cruise conditions. These are shown in Table 2.

It was decided that 1500 rpm would often be the engine speed in stop-and-go traffic, that 3000 rpm would often be attained at cruise

conditions, that 4500 rpm would be experienced under moderate acceleration through the gears and high-speed cruise, and that 6000 rpm should be included because of the high rpm capabilities of the engine.

Table 2. R100 Cruise Conditions (Level Ground)

Gear	Indicated Speed	Engine RPM	Manifold Vacuum (in.Hg)
4	40	2200	16
4	50	2800	14
4	60	3200	13.6
4	70	3800	11.5
4	80	4300	9.5

Load

The dynamometer used performed satisfactorily under most conditions except for leaking under very low rpm and high loads. The dynamometer was able to hold the Mazda engine at full throttle at about 2000 rpm.

The loads decided upon were equal steps of 5, 10, and 15 inches of mercury manifold vacuum. This gave a fairly wide range of load conditions without pushing the engine to its limits. The heavier load would be encountered in the automobile under hard acceleration.

Ignition Timing

The engine was equipped with a vacuum advancing mechanism for each distributor. It was decided that trying to change the advance curve characteristics was out of the question, but changing the advance

at idle would have the effect of shifting the advance curve completely. Thus, it was decided to test the engine with five degrees of retard and 10 degrees of retard from factory conditions simultaneously for both distributors. The distributors were not advanced from normal for fear of creating abnormally high combustion pressures (especially when the engine was running on gasoline) and damaging the engine (6).

Retarding the spark was easily accomplished at idle using a conventional timing light.

Fuel Mixture

Fuel mixture proved to be the most difficult parameter to control effectively, particularly when running on gasoline. It was decided that the effects of variations of the other parameters should be investigated when fuel mixture was approximately stoichiometric. That is, changes in spark retard should be made while air-fuel ratio was held constant, etc. This was often hard to do and resulted in the rerun of many data points because of incorrect air-fuel ratios.

The effects of air-fuel ratio itself on exhaust emissions was to be investigated as well, with rich mixture settings through an entire test run at various engine speeds and loads, and lean mixture settings through the same variations of engine speed and load.

The factory carburetor jets were slightly richer than stoichiometric, although they did provide some stoichiometric data points. In order to obtain lean gasoline runs the jets were filled with solder and redrilled with a smaller drill size. This was done because replacement jets of different sizes were not readily available for the engine.

Enriching the gasoline mixture was accomplished by drilling out the carburetor jets to a larger size and/or closing the carburetor choke butterfly.

Adjusting the air-fuel setting when running on natural gas was quite simple. It could be done in either of two ways, or a combination of both. The pressure regulator downstream of the gas meter could be adjusted to affect the mixture, and the mixing venturi on the Impco, natural gas air intake could also be adjusted.

The stoichiometric air-fuel ratio for gasoline (considering gasoline as pure octane) is 15.2/1. The stoichiometric air-fuel ratio for natural gas (as pure methane) is 17.2/1.

Alternate Fuels

As mentioned before, the engine had a dual fuel capability and it was quite simple to switch from gasoline to natural gas. When the data were run, the majority of the natural gas data were taken first and then the gasoline runs were made. Reruns of the data points that were unsatisfactory were then made, in no particular sequence.

Final Testing Program

When the parameters to be investigated were decided upon and the degree of variations was determined, the final testing program began to take shape. The runs to be made are shown in Table 3.

As can be seen from the table, the engine was run at four speeds under each of three loads for each combination of timing, mixture, and type of fuel. This gives a minimum total of 120 data points, and it was felt that this would be sufficient to draw some well-founded conclusions

about the engine's performance and emissions with alternate fuels. With the goal of running the engine under these conditions in sight, data taking was begun.

Table 3. Data Points

rpm	Load	Timing	Mixture	Fuel
4 ×	3	Standard	Stoichiometric	Natural Gas
4 ×	3	Standard	Lean	Natural Gas
4 ×	3	Standard	Rich	Natural Gas
4 ×	3	5° Retard	Stoichiometric	Natural Gas
4 ×	3	10° Retard	Stoichiometric	Natural Gas
4 ×	3	Standard	Stoichiometric	Gasoline
4 ×	3	Standard	Lean	Gasoline
4 ×	3	Standard	Rich	Gasoline
4 ×	3	5° Retard	Stoichiometric	Gasoline
4 ×	3	10° Retard	Stoichiometric	Gasoline

Initially the test program was to be run with the engine's thermal reactor in place and it was hoped that it could be used to reduce pollutants with natural gas as well as gasoline. Many data points were run on gasoline and a few on natural gas with the thermal reactor in operation.

When about 90 hours had been put on the Wankel engine in the test stand, there was a rather unfortunate development. It was discovered that water was coming out of the exhaust ports in large quantities. The only conclusion that could be reached was that an internal engine part had failed. There was nothing else to do but disassemble the engine and locate the problem. This turned out to be a rather

time-consuming process. Certain special tools were needed to dismantle the engine and these were obtained readily from a local Mazda dealer.

Although this seemed to be a tragic development, it really turned out to be an educational experience, since it provided an opportunity to examine the workings of the Wankel very closely.

Disassembly was quite simple once the proper tools were obtained, and consisted of an unstacking of the parts. The major parts of the engine laid out are shown in Figure 10. From the rear of the photograph the components are as follows: front and rear rotors, eccentric shaft, intermediate housing, rear rotor housing, and rear engine housing. The thermal reactor is also included in the right of the picture.

The factory shop manual includes many procedures for a thorough inspection of all the engine parts, and these procedures were carefully carried out. The cause of the water leakage was not immediately apparent, but eventually it was discovered that both rotor housings had shrunk in the area of the spark plugs. That is, the depth of the housings was about .010" less than it should be, and since the engine depends on "O" rings for water sealing in this area, that may have been enough to cause the leakage. The cause of this shrinkage has been credited to the poorly-designed laboratory cooling system. Temperature control of the water was not satisfactory, and the engine had a tendency to overheat under certain conditions. The cooling system would allow the engine to run right at the boiling point (212°F) for a short period and then would allow cold water to enter the engine from the holding tank, thus bringing the coolant temperature down to about 140°F in a

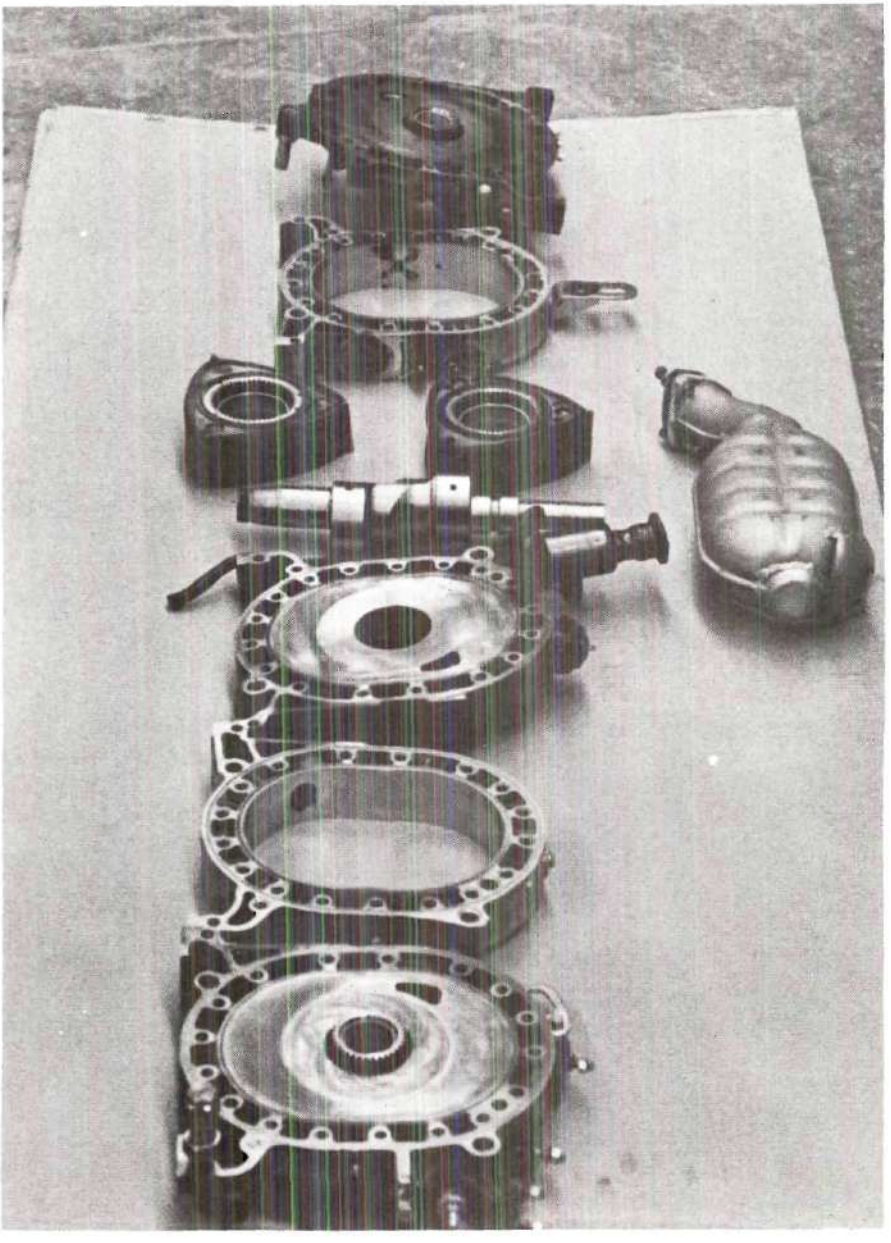


Figure 10. Exploded View of Wankel Engine.

matter of seconds. Steps were taken to rectify this problem when the engine was reinstalled, but the system is still not completely satisfactory. At any rate, it was decided that this thermal shocking of the engine resulted in the deformation of the rotor housings. Toyo Kogyo had worked on thermal stress problems of this nature during the development of the engine and apparently did not encounter similar problems, but perhaps the test conditions were different (6). In view of this shrinkage, both rotor housings were replaced with new parts.

An additional problem came to light when the engine was disassembled. The rear housing seemed to have been "scuffed" in some way by the rotor. Also it appeared that there was a crack starting from the intake port. It was decided that the scuffing must have resulted from an improper alignment of the internal ring gear on the rear rotor. Thus the rear rotor and rear housing were also replaced.

The seals used on the rotor were all examined and found to be well within factory specifications. This was heartening to know, since development of the Wankel was hampered so long with seal wear problems. Apparently Toyo Kogyo has solved this problem.

Reassembly of the engine was quite easy and it started right up and ran as well as before.

In view of the new parts in the engine, it was decided to discard the old data and start anew. Also, since performance of the thermal reactor on natural gas had not been up to expectations, the reactor was removed and replaced with the specially-made steel exhaust reactor.

Test Procedure

With the engine in good operating condition and all the instruments functioning properly, the final testing could be carried out. From the time the engine was reassembled until all the data were collected, another 50 hours of time was put on the engine.

Once the laboratory was prepared for data collection, many points could be taken quite rapidly in succession. The first thing that had to be done was warming the instruments up and giving them an initial calibration. Usually the Sun tester and the Olson-Horiba instruments were left at "standby" all the time, but in the event they were shut off, one to two hours would be required for them to stabilize. The Beckman-HC analyzer was always shut off overnight to conserve the fuel and air supply. After the hydrogen flame was lit, it would require about one hour for stabilizing.

When all the instruments were warmed up, the sample pump would be turned on and the instruments would be calibrated one at a time. The Olson-Horiba instruments would usually be calibrated first. When calibrating, the most important point was to make certain that the pressure and flow rates of the calibration gases going through the instrument were the same as the settings made when the actual exhaust samples were flowed through the instrument.

The calibration of the NO instrument will now be described. First, the four-way valve was turned to "zero," and flow of zero gas through the instrument was set at 6 CFH as registered on the rotameter by adjustment of the NO bypass valve. The sample cell pressure gauge

should then have read 8 in. W.G. If not, the rotameter needle valve and bypass valve would be readjusted. When 6 CFH and 8 in. W.G. were obtained, the zero point was set on the instrument (with the range selector switch in the proper position). The four-way valve was then switched to "span" and the span gas allowed to flow through the instrument. Flow of the span gas was then set at 6 CFH, and the pressure should have been 8 in. W.G. The span point could then be set on the instrument. The four-way valve was then switched to "sample" and a measurement of the exhaust sample was made, provided the flow was also set at 6CFH and the sample pressure was 8 in. W.G.

Next, the calibration of the CO_2 instrument was carried out. The steps taken were identical to those necessary for calibration of the NO instrument, but of course the valves used were different. Again it was most important to calibrate the instrument with the span and zero gases flowing at the same rates as the sample gas. These rates were the same as for the NO instrument; 6 CFH for the flow rate, and 8 in. W.G. for the sample pressure.

Calibration of the Beckman analyzer followed. Care was taken to see that the fuel pressure was set at 30 psig and the air pressure was set at 7 psig (these pressures were read on gauges inside the instrument). A four-way valve was provided for the hydrocarbon analyzer as well, and the zero gas flowed through the analyzer first. The flow rate was set at 6 CFH on the hydrocarbon rotameter, and sample pressure (as read on a gauge inside the instrument) was set at 3.5 psig with the sample pressure regulator. With these conditions set and the zero gas

flowing, the zero point was set on the instrument. Next, the same flow and pressure conditions were set with the span gas flowing, and the desired span point was set. The four-way valve could then be set to "sample," and the same flow conditions set for the analysis of the exhaust gas.

When the above procedures were completed the Sun instrument could be calibrated. This was a simple operation since internal calibration was provided. The zero and span points were set for the hydrocarbon meter and the CO meter and the calibration of the entire sampling train was complete.

While the sampling train was being calibrated the engine was usually being warmed up. When the calibration was complete, the desired data conditions could then be set. This was done by varying the dynamometer load and the throttle setting the obtain the correct rpm and manifold vacuum.

After the engine had stabilized at the right rpm, air-fuel measurements were taken. These procedures varied according to which fuel was being burned. When gasoline was the fuel, a note was made of the weight of the fuel tank and a stop watch started. The flow rate of air into the engine was then read on the manometer. After this was done, room temperature and barometric pressure were recorded. After these items were noted, the emissions instrumentation was read. Readings were made of the Beckman HC, Olson-Horiba NO and CO_2 and Sun HC and CO, and recorded. A torque reading was then taken from the dynamometer scale. Next, the engine oil temperature and water temperature were recorded.

When all this was done, there had usually been enough gasoline burned to move the scale enough to make an accurate measurement. The final gasoline weight and the time were recorded. When this was complete, the conditions for the next data point could be set up.

The only difference in recording the mixture data when running the engine on natural gas was that the weight of gasoline was not recorded. Instead, the dry gas meter was read. The stop watch was started when the meter's five cubic foot needle reached one of the graduations on the volume scale, and the needle was usually allowed to complete two revolutions (which represented ten cubic feet) before the watch was stopped. Recording of other data was the same as when gasoline was used.

The preceding section has described in detail the procedure used to run a typical data point for the Mazda engine. Small changes in procedure were sometimes made according to different conditions and different variations of parameters, but the majority of the runs used the same procedure and could be carried out quite rapidly.

Sources of Error

Errors can come from many sources in the data for this thesis. The most important errors probably resulted from equipment malfunctions or irregularities, but there could be a good deal of human error involved as well.

Some of the simplest errors may have resulted from the equipment's inability to hold a test condition. That is, the engine rpm could easily have drifted from the desired value, the dynamometer load

could have changed, or engine temperature could have varied. Engine instrumentation could also have contributed to these errors. Engine speed was monitored by a good quality electric tachometer which was checked for agreement early in the program, with a mechanical tachometer attached to the end of the dynamometer shaft. Agreement was found to be within 50 rpm. Changes in engine speed were quite noticeable in the laboratory because of the changes in pitch of the engine sound. Thus, engine rpm drifts could usually be corrected. However, as most of the experiments were run with only one person in the laboratory it was impossible to be certain that engine speeds were scrupulously maintained. It is improbable that errors of more than 100 rpm occurred often, and errors of more than 200 rpm almost never.

Engine load had a tendency to vary under certain conditions, mostly due to variations of inlet water pressure to the dynamometer. These occurred partially because of cycling in the engine's cooling system since the dynamometer was supplied from the same line. A water pressure regulator was later connected to the dynamometer inlet but even this did not stop the fluctuations entirely. It should be noted that changes in load were usually accompanied by changes in rpm. The gauge for measuring manifold vacuum was a good quality automotive type gauge, but, of course, greater accuracy could have been obtained with a manometer. It is doubtful that errors in load in excess of 1" Hg vacuum were common.

Variations in engine temperature can also affect exhaust emissions (11). Every effort was made to maintain engine water temperature

between 180-190°F, but this was not always possible since the cooling system did not lend itself to fine temperature control under all test conditions.

Variations in laboratory ambient conditions can also affect exhaust emissions (16). Since it was impossible to run all the tests for this thesis in a single day or on days with the same temperature and barometric pressure some error may have resulted. It is expected that this error will be small.

The majority of errors probably resulted from the emissions instrumentation and the use of it. The equipment used was of high quality, but every instrument had at least a minor malfunction on occasion, and it is possible that small irregularities in the instruments could cause errors. When many data points were run in rapid succession, the instruments were usually recalibrated fairly often to make certain they had not drifted. If the manufacturers' specifications are assumed, the Beckman HC analyzer could be expected to have errors no larger than about 60 ppm hexane, the Olson-Horiba NO about 40 ppm NO, and the CO_2 instrument about .15 per cent CO_2. The Sun instrument was liable to have a much larger error, however, since its accuracy is about ±10 per cent of full scale, so errors as large as 0.5 per cent CO could occur. It will be seen in the data that the CO readings sometimes appear erratic.

Some errors in emissions concentrations may have resulted from contamination in the system. The filters were cleaned often and the system was backflushed with clean, compressed air after every use, but

particulate deposits could be found on some of the system tubing, particularly when the engine was run on gasoline. Contamination would probably result in higher emission readings than were actually present, since particles might have absorbed hydrocarbons or other gases.

Another point should be considered about instrument calibration. Since the calibration relied on span and zero gases that could not really be checked for accuracy, some small errors might have resulted from the setting of zero and span points. This is unlikely since the gases were certified to be of given concentrations by reputable suppliers, but the possibility of small errors should not be entirely ruled out. Certified accuracy of these gases has already been mentioned.

Another area where errors could be made is the calculation of air-fuel ratio. A good deal of confidence can be placed on air flow data since high quality equipment was used. The degree to which the pressure differential of the laminar flow element could be read was greater than necessary (i.e. to the nearest .001 in. water). Accurate calibration curves were supplied with the laminar flow element, as were corrections for temperature and pressure. The flow element manufacturer certifies an accuracy of ±0.5 per cent. Laboratory temperature was measured with a good quality thermometer to the nearest 1°F and pressure was measured with a barometer accurate to at least 0.01 in.Hg. The only sources of significant error with the air flow would be a leak in the hose connecting the flow element to the carburetor or human error in misreading the manometer.

Errors could have been made in measuring natural gas flow, but these would probably be due to human error, since dry natural gas meters are quite accurate.

Errors could also have been made in measuring gasoline flow, since the scale used for weighing the fuel supply was quite old and may have been abused. Therefore, the engine was allowed to use as much gasoline as possible for a given data point, so that erratic motion of the scales pointer would be eliminated. Readings on the scale were made to the nearest .01 pound, and usually at least 0.5 pound of fuel was burned.

It can be seen from the above that there were many areas in these experiments where errors could be made, but great care was taken to minimize errors wherever possible. Had time permitted, all of the tests would have been run two or three times and the average emissions values used. The National Academy of Sciences has reported that emissions tests on automobiles can be quite erratic, sometimes varying as much as ±50 per cent of average values due to changes in instrumentation, emission control systems, and variations in test procedure (8). The data in this thesis should be considerably more accurate than that.

CHAPTER IV

RESULTS

Data Taking and Data Reduction

As mentioned earlier, several false starts were made in taking data, and after the bulk of the runs was made, some had to be taken over because of poor correlation with other points. In fact, the first run to be used in the results was run No. 110, the first 109 being discarded. In excess of 270 total runs were made, and many different relationships among the parameters can be found from all this data. In the interest of simplification not all the points will be used, but only those leading to the most significant conclusions. All the data points will be included in table form in Appendix C, however.

One of the most important parameters to be investigated was the air-fuel ratio. Calculation of this was rather involved, and procedures differed according to whether natural gas or gasoline was being burned. An example of air-fuel calculations for both fuels is given in Appendix A. These calculations were made to four significant figures.

When an engine is being run at mixtures other than stoichiometric, Federal test procedures require that corrections for dilution be made, so that emissions do not appear to be reduced when in fact concentrations are lower merely due to excess air in the exhaust. Each pollutant (NO,CO,HC) has to be corrected for dilution, and all data

presented in this thesis have been corrected. A sample calculation of the correction appears in Appendix B.

Meaningful Data Relationships

Six sets of graphs have been generated to display the results of the tests on the Wankel engine. Each set will be considered separately and all will be discussed in the next section.

A. Emissions Variations with Engine Speed

The exhaust emissions of the Wankel engine vary significantly with engine rpm. This fact is shown in Figures 11, 12, and 13. Data for these curves is included in Appendix C in Tables C1, C2, and C3, respectively. Figure 11 shows emissions variation with a constant load of 15 inches vacuum on the engine and a fairly constant mixture at nearly stoichiometric conditions. Timing was set to factory specifications. Figure 12 shows emissions variation with a constant load of 10 inches vacuum, stoichiometric mixture, and factory timing. Figure 13 shows emission variations with a constant load of 5 inches vacuum, stoichiometric mixture, and factory timing. Note that these figures include curves for both natural gas and gasoline.

B. Emissions Variations with Engine Load

For the next set of curves, engine speed is a constant and engine load is a variable. Again, mixture was maintained at stoichiometric conditions as closely as possible, and timing was set at factory specifications. Figure 14 shows emissions variation at loads of 5, 10, and 15 inches vacuum (6, 10, and 15 inches for gasoline) at 1500 rpm. Data for these curves are shown in Table C4.

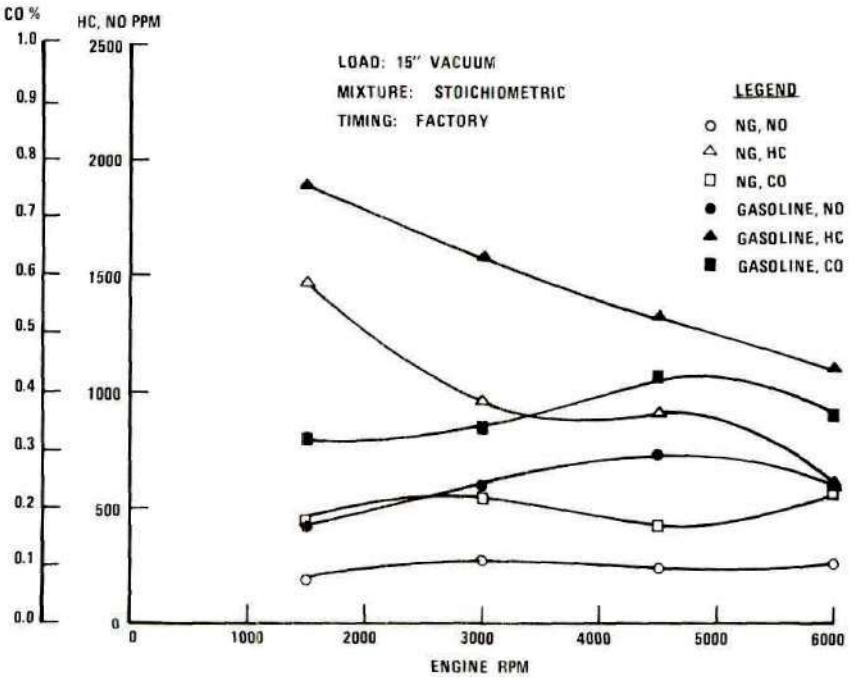


Figure 11. Emissions Variations with Engine Speed.

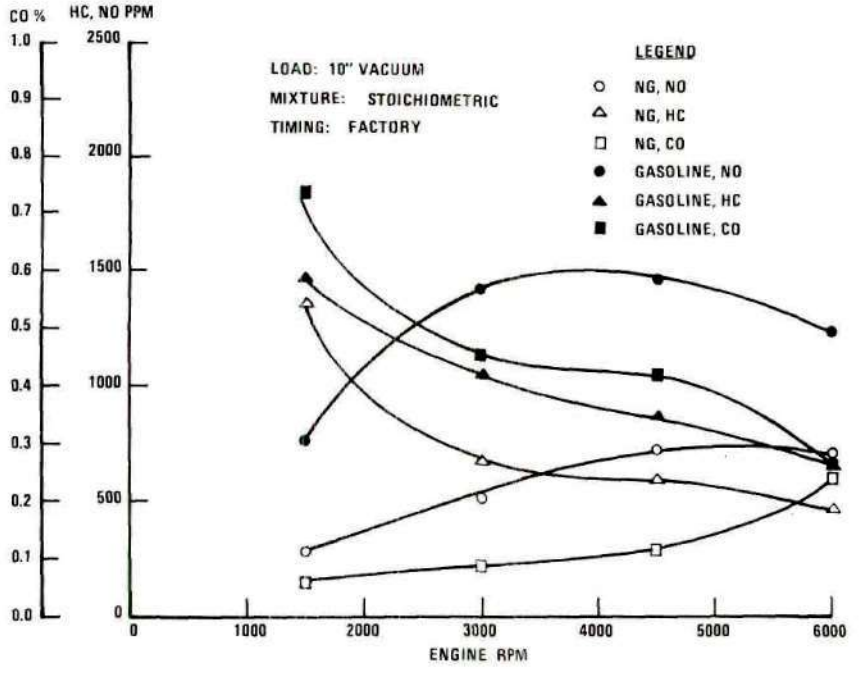


Figure 12. Emissions Variations with Engine Speed.

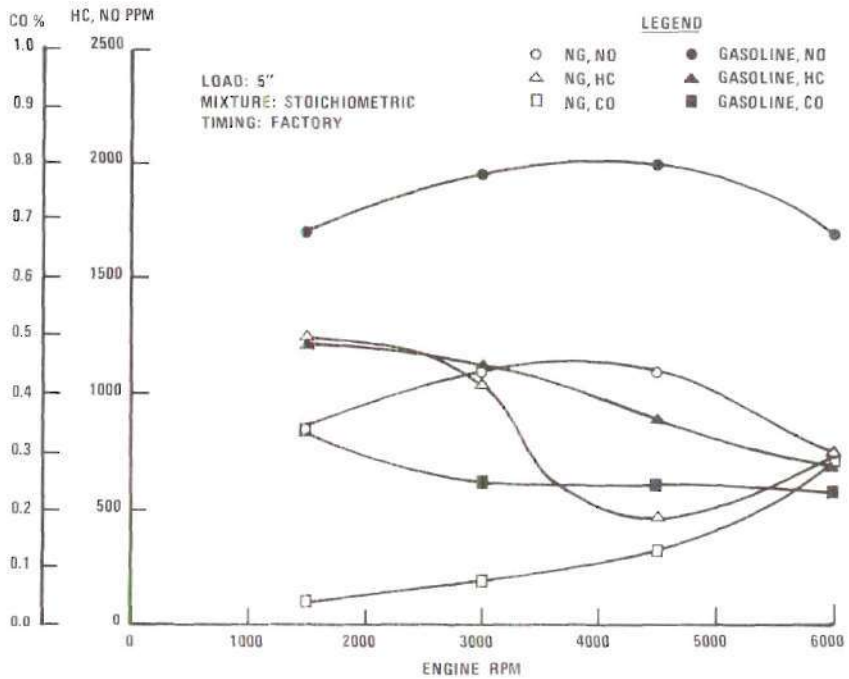


Figure 13. Emissions Variations with Engine Speed.

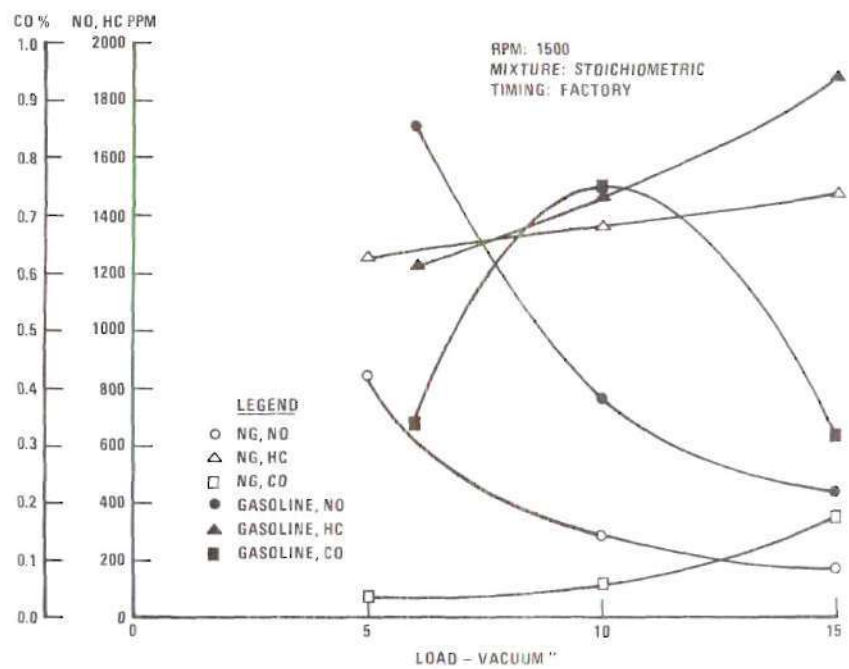


Figure 14. Emissions Variation with Engine Load.

Figure 15 shows the same information for engine speed of 3000 rpm and data are shown in Table C5. Figure 16 shows the same information for 4500 rpm, with data displayed in Table C6, and Figure 17 shows the information for 6000 rpm, with data shown in Table C7. Again, curves are included for natural gas and gasoline.

C. Emissions Variations with Ignition Timing

The third set of graphs illustrates the effects of changes in ignition timing on exhaust emissions. Initially, 12 graphs were drawn to display this information, and the data are contained in Tables C8 through C19. Each table represents the data for conditions of constant load, constant engine speed, stoichiometric mixture, and variation of spark retard at idle. Data are included for 0 degrees retard from factory specifications, 5 degrees retard and 10 degrees retard. After the graphs were drawn, it was decided that the inclusion of all the graphs in this paper was unnecessary, since the general trends could be seen with fewer graphs. Therefore, only five graphs will be included.

Figure 18 shows the variation of exhaust emissions with ignition timing for an engine speed of 1500 rpm, an engine load of 10 inches vacuum, and a stoichiometric mixture (approximately). Curves are shown for gasoline and natural gas, and data are shown in Table C9. Figure 19 shows emissions variation with timing for 3000 rpm, 10 inches vacuum load, and stoichiometric mixture. Data for Figure 19 are displayed in Table C12. Figure 20 shows emissions variation with timing for 3000 rpm, 5 inches vacuum load, and stoichiometric mixture. Data for Figure 20

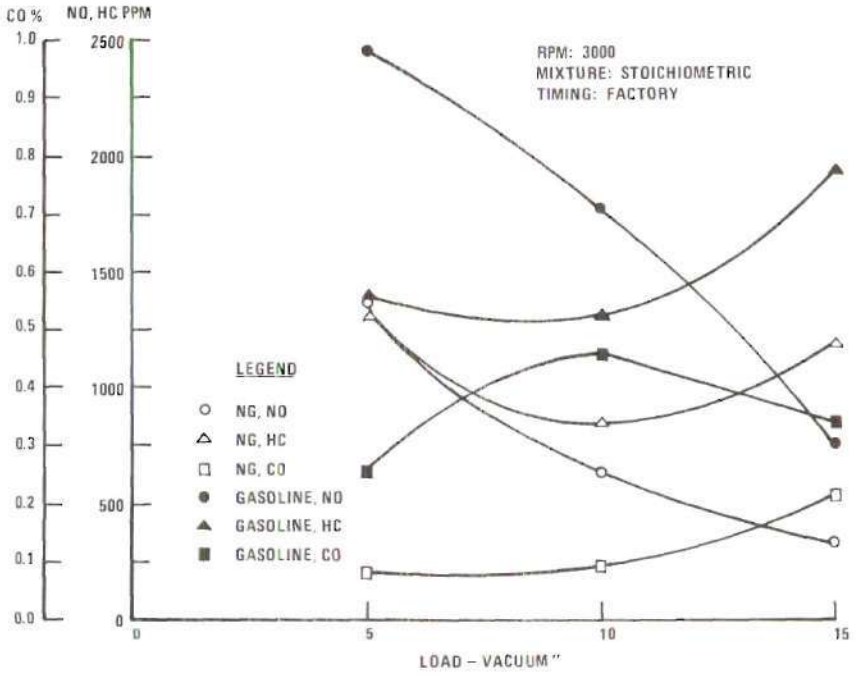


Figure 15. Emissions Variation With Engine Load.

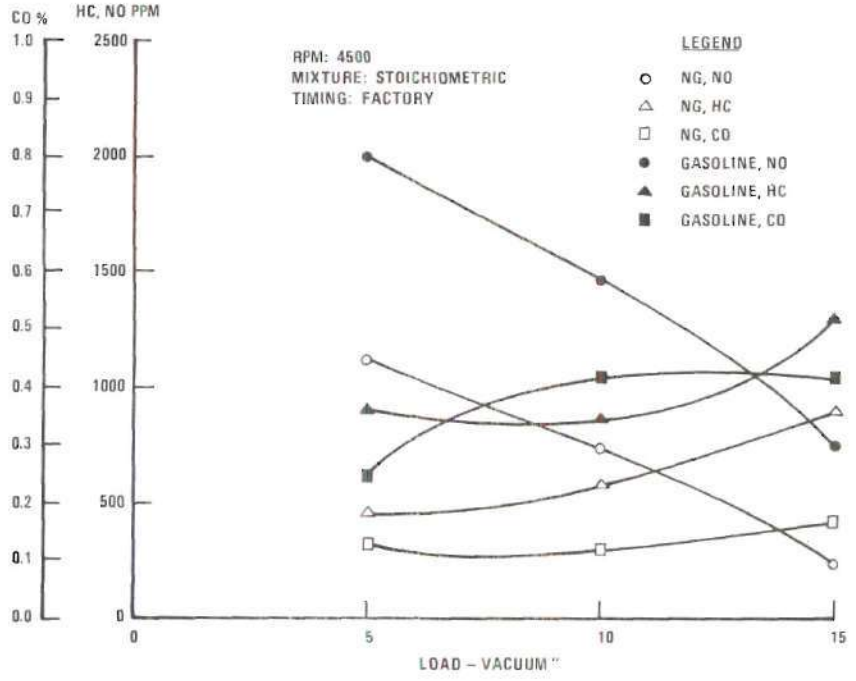


Figure 16. Emissions Variation with Engine Load.

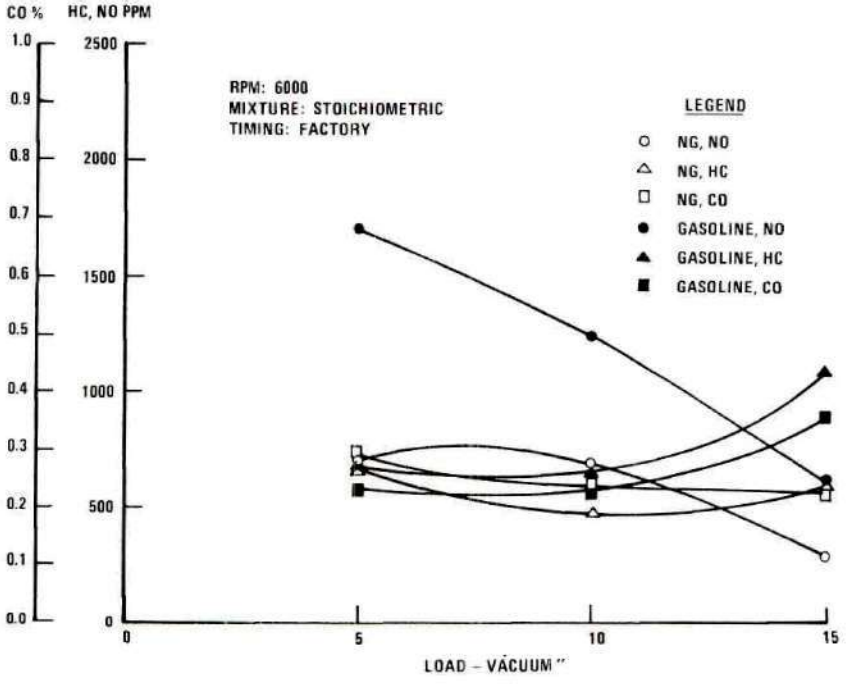


Figure 17. Emissions Variation with Engine Load.

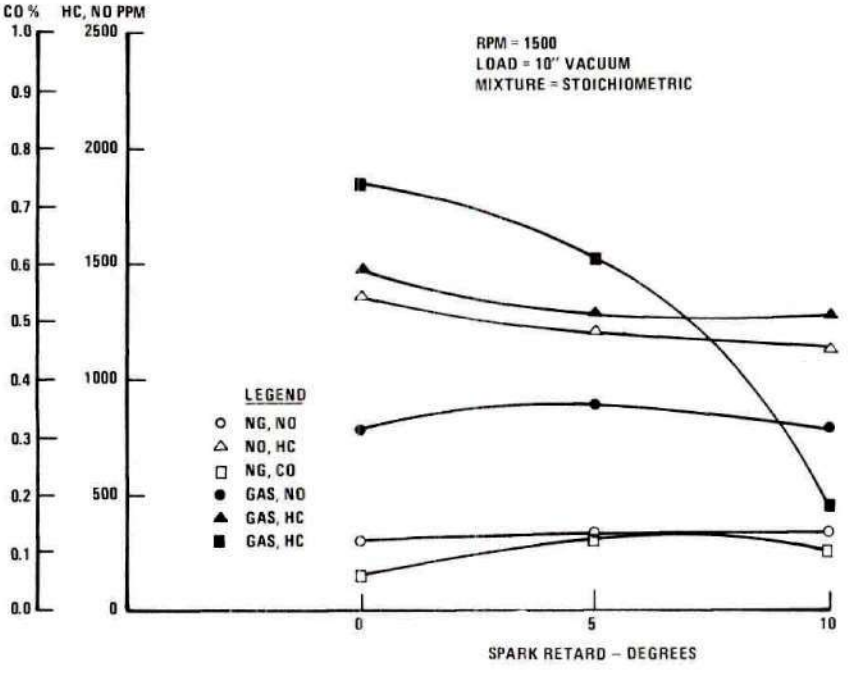


Figure 18. Emissions Variation with Timing.

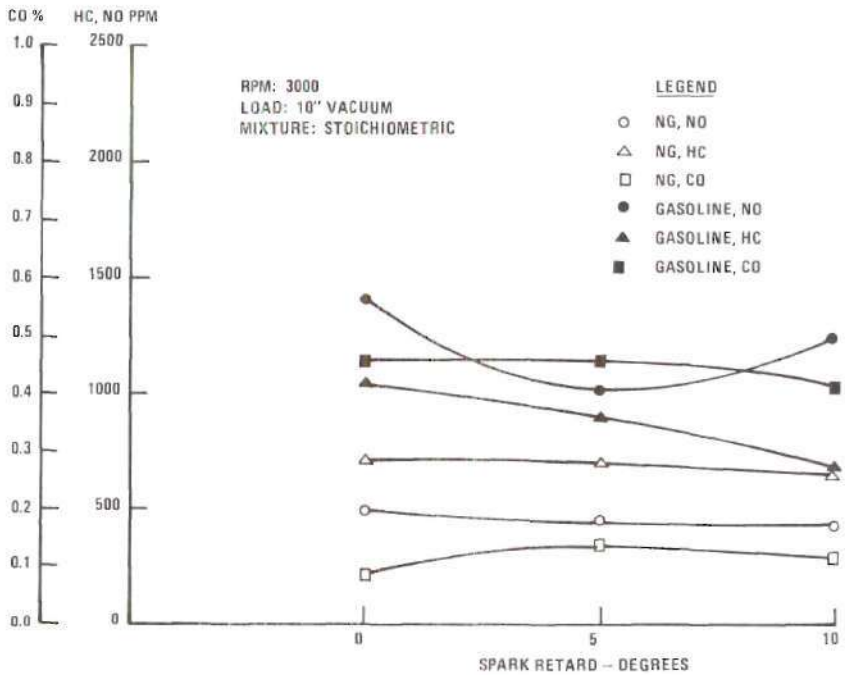


Figure 19. Emissions Variation with Timing.

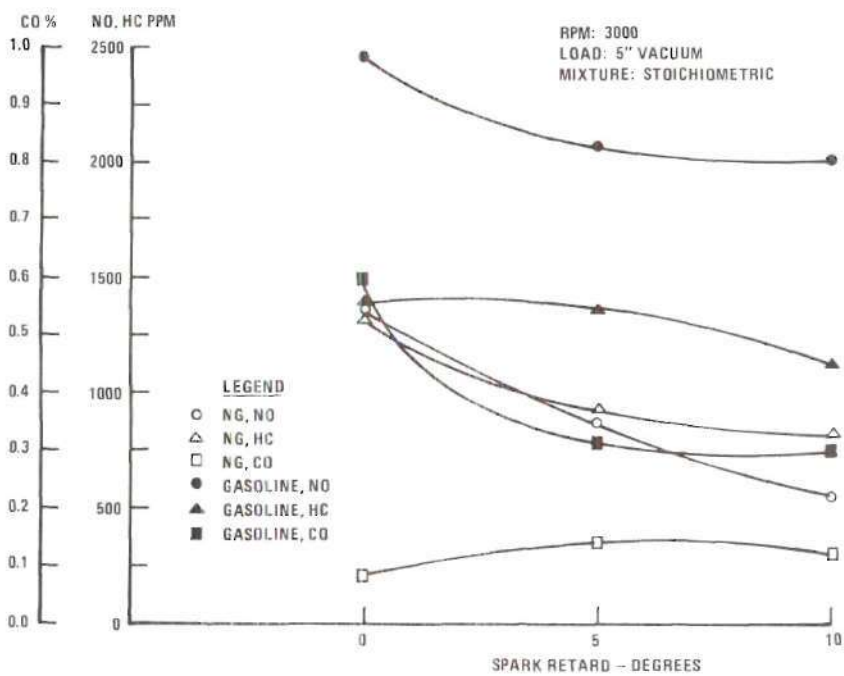


Figure 20. Emissions Variation with Timing.

are shown in Table C13. Figure 21 shows emission values for timing variation with conditions of 4500 rpm, engine load 10 inches vacuum, and stoichiometric mixture. Data for Figure 21 are included in Table C15. Figure 22 shows emissions variation for 6000 rpm, five inches vacuum, stoichiometric mixture, and data are shown in Table C19.

D. Emissions with Mixture Variation

The fourth set of graphs was drawn to show how exhaust emissions are affected by the air-fuel mixture. Again, 12 graphs were drawn initially, and showed clearly that more data needed to be run with natural gas, since the mixture range was not wide enough. In the interest of time, it was decided to run data for only five graphs since the important trends can easily be seen from these. Data for all the curves are included, however, and may be found in Tables C20 through C31.

Figure 23 shows the variation of pollutants with air-fuel mixture for a constant engine speed of 1500 rpm, a constant load of 10 inches vacuum, and ignition timing set to factory specifications. Data for Figure 23 are displayed in Table C21. Figure 24 shows the variation of emissions for 1500 rpm, engine load of five inches vacuum, and standard timing. Data for Figure 24 are shown in Table C22. Figure 25 shows effects of mixture change for 3000 rpm, 15 inches vacuum, and standard timing. Data for Figure 25 are included in Table C23. Figure 26 shows emissions variation for 4500 rpm, 10 inches load, standard timing, and the data are shown in Table C27. Figure 27 displays variations with mixtures for 4500 rpm, 5 inches load, and standard timing, and the data are shown in Table C28. Again, curves for natural gas and gasoline are displayed together for comparison purposes.

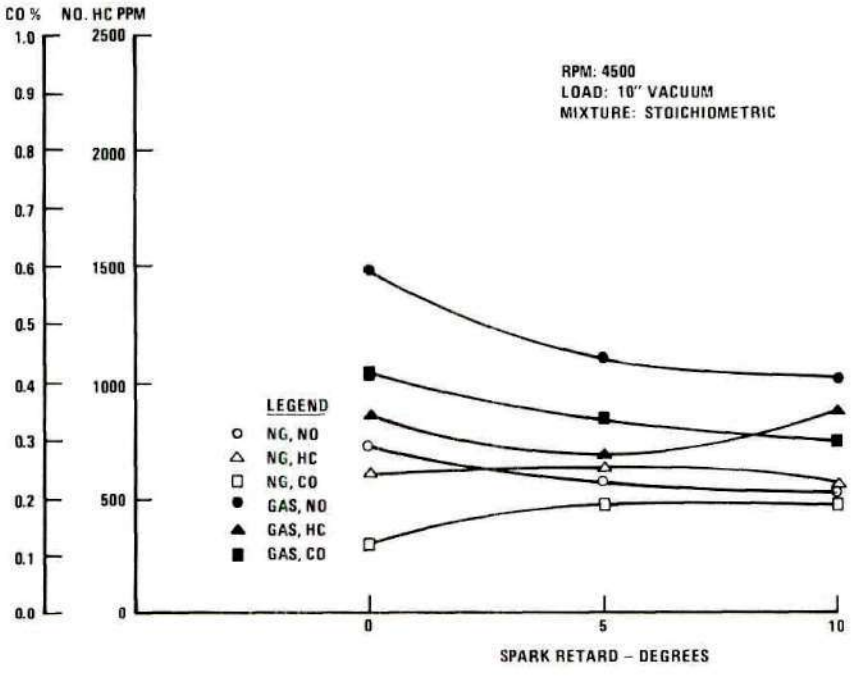


Figure 21. Emissions Variation with Timing.

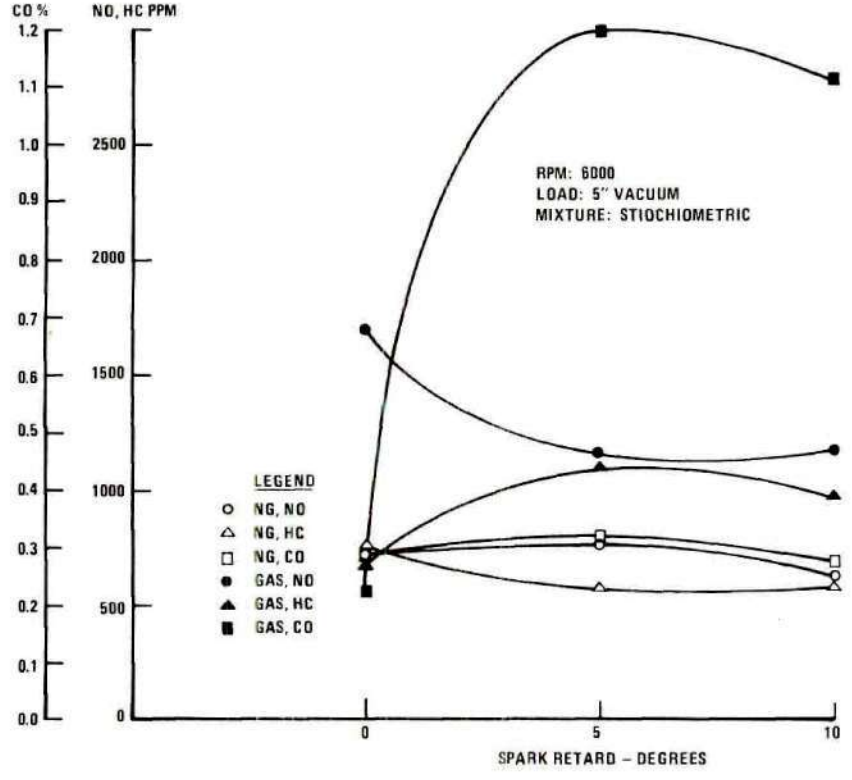


Figure 22. Emissions Variation with Timing.

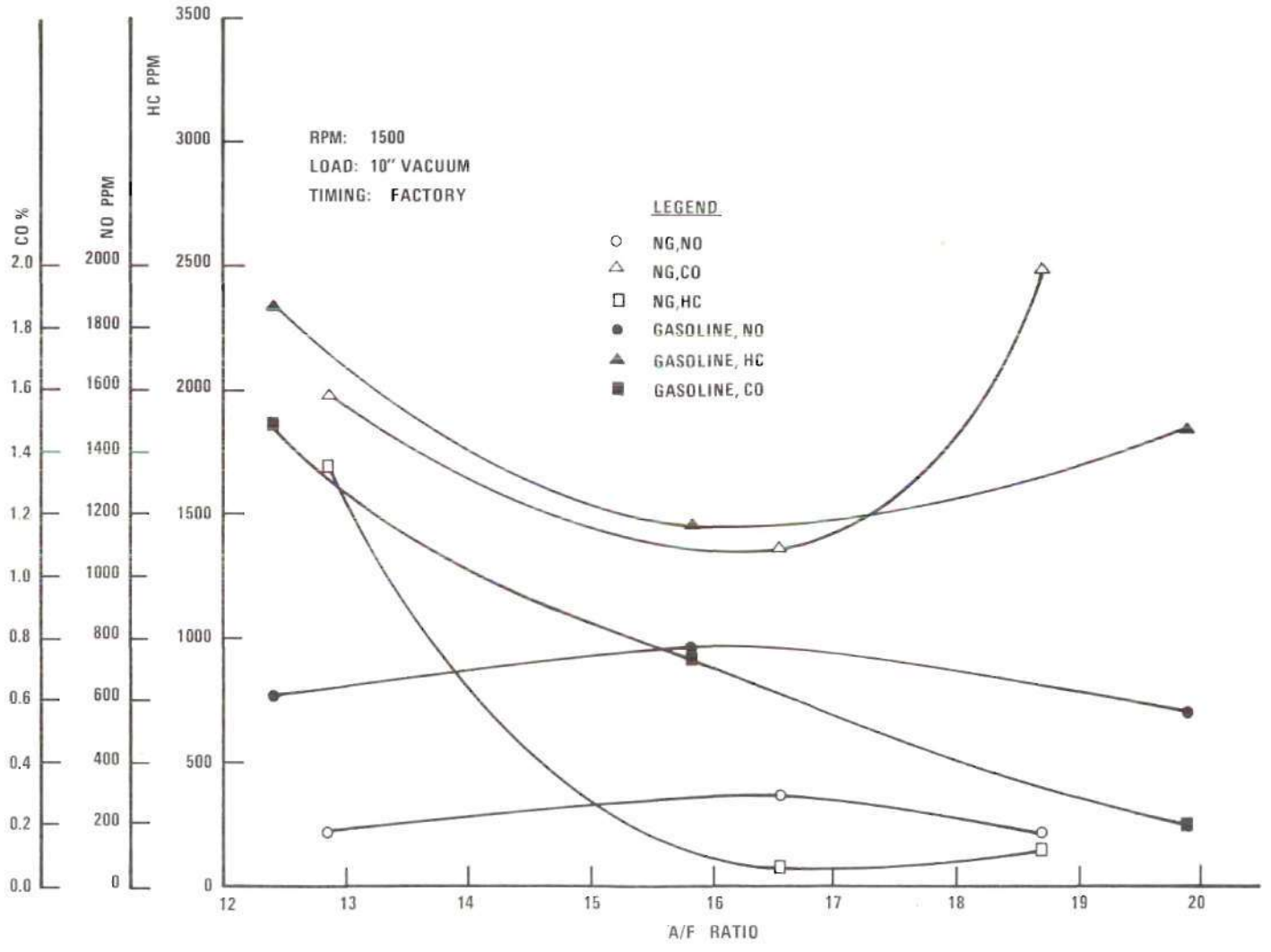


Figure 23. Emissions Variation with Fuel Mixture.

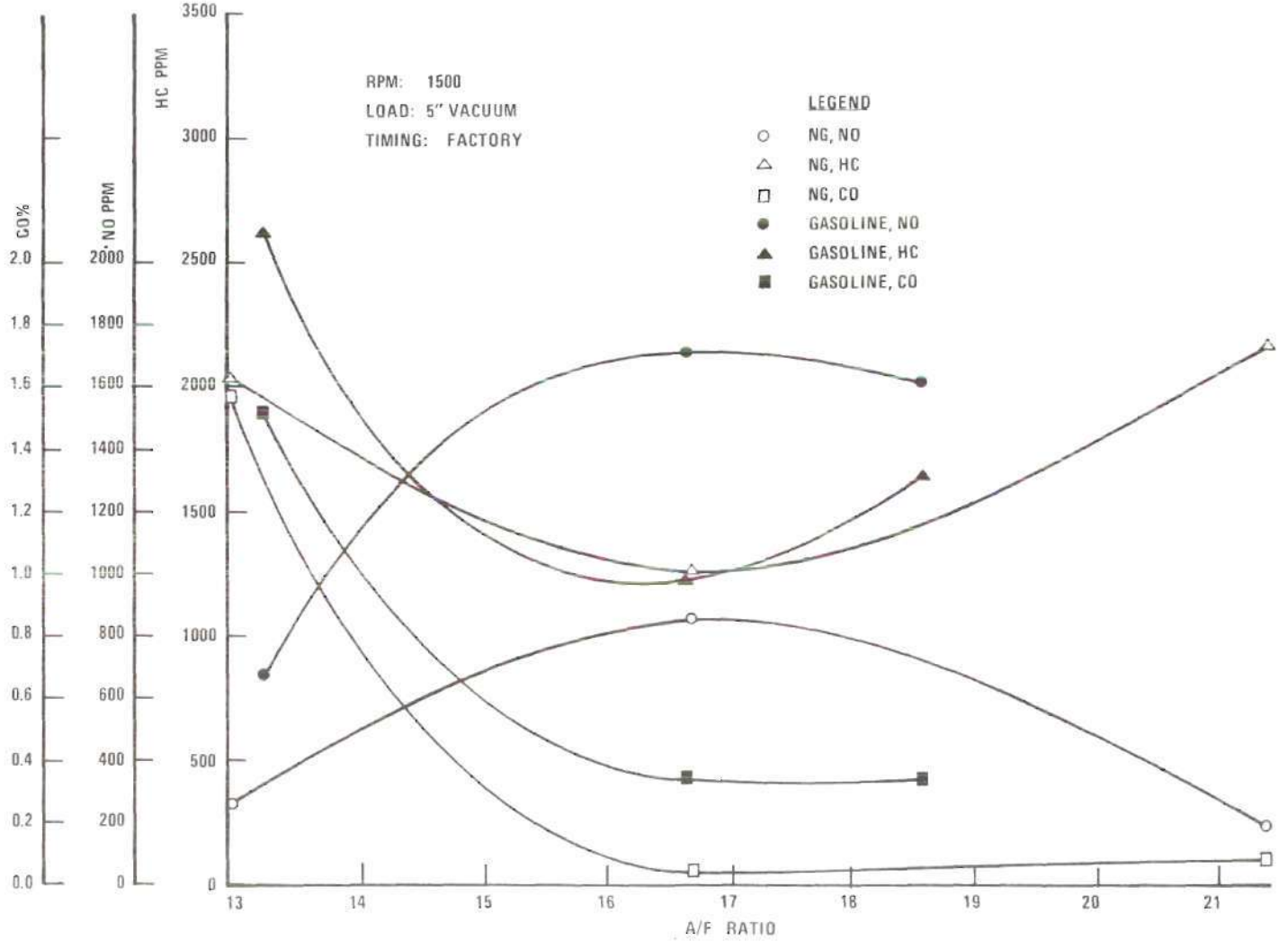


Figure 24. Emissions Variation with Fuel Mixture.

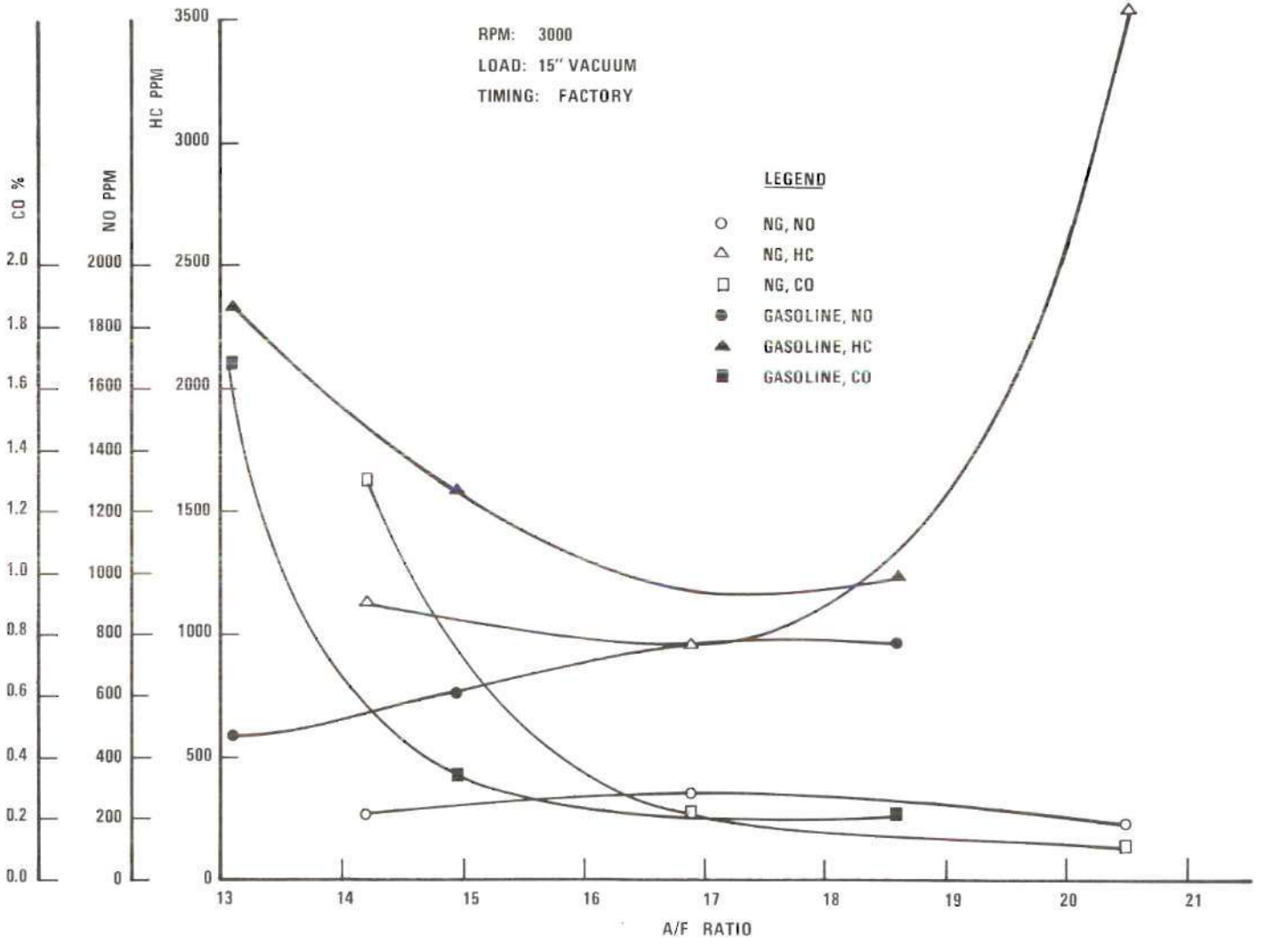


Figure 25. Emissions Variation with Fuel Mixture.

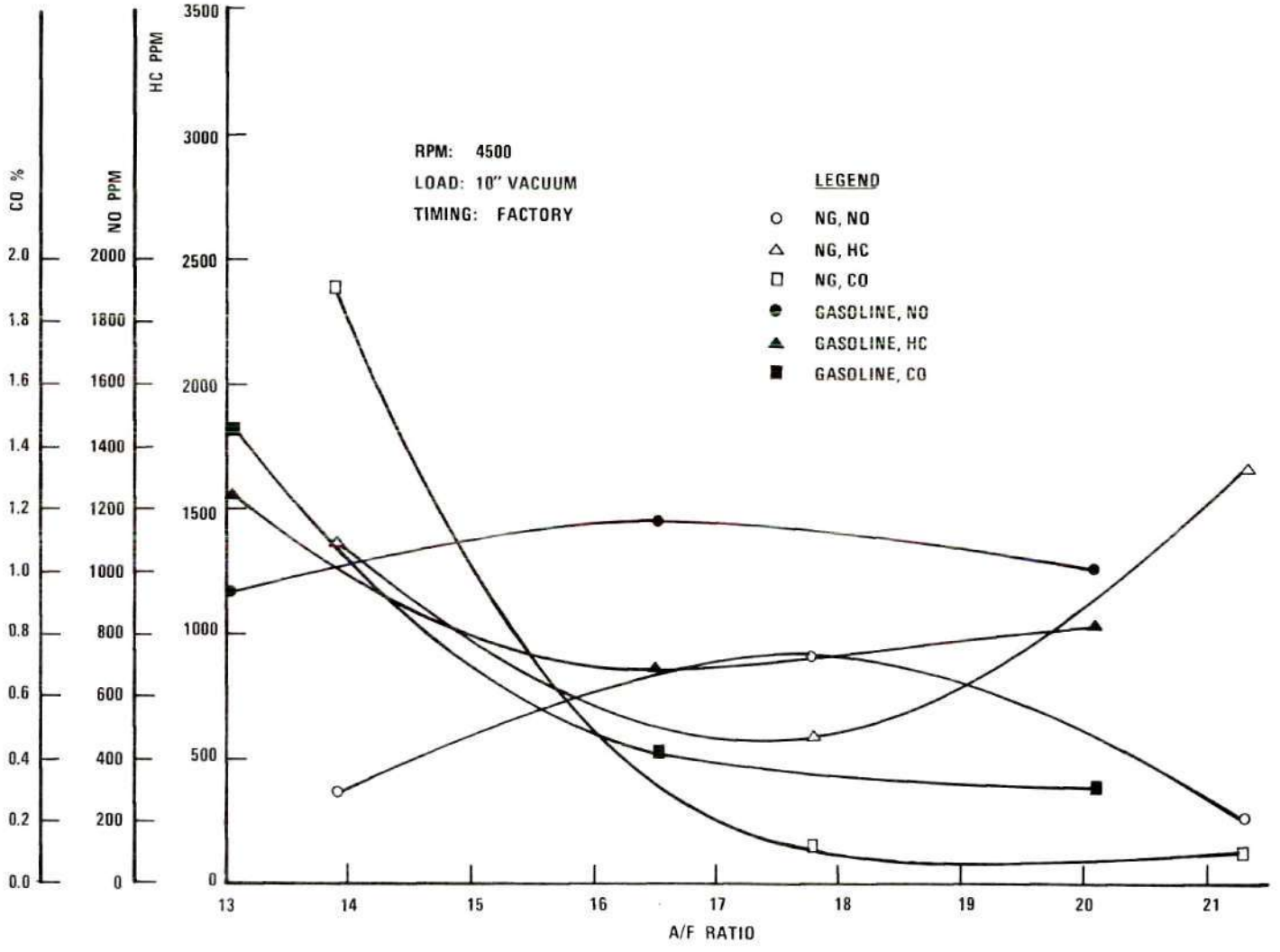


Figure 26. Emissions Variation with Fuel Mixture.

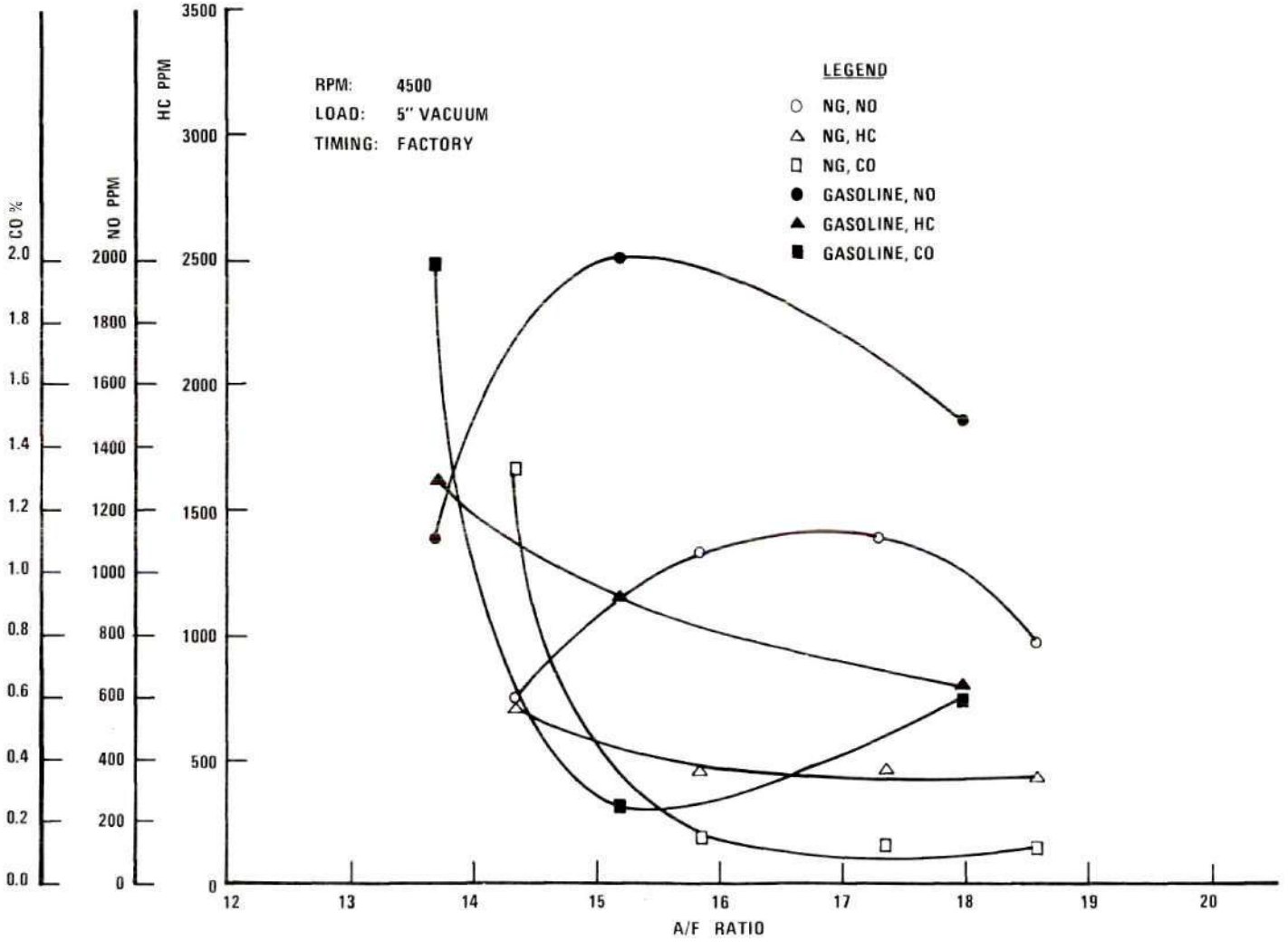


Figure 27. Emissions Variation with Fuel Mixture.

E. Horsepower Variations with Different Fuels and Mixtures

The fifth set of graphs is included to illustrate the effects on engine power of switching from gasoline to natural gas. Relative power levels are shown on these graphs, and the mixtures are simply designated "rich," "stoichiometric," and "lean." The points are generally quite close together.

Figure 28 shows variation in horsepower with rpm for a constant vacuum of 5 inches using various air-fuel mixtures for both natural gas and gasoline. Data for this graph are included in Table C32. All torque readings were made directly on the hydraulic dynamometer, and were multiplied by engine rpm and then divided by a "dyno constant" of 6000 to obtain brake horsepower. Figure 29 shows the same information for an engine load of 10 inches vacuum, and Figure 30 shows the same information for a load of 15 inches. Data for Figure 29 are shown in Table C33, and data for Figure 30 are shown in C34.

F. Horsepower Variations with Timing

Tables C35 through C38 contain data displaying the effect on engine horsepower of changing the ignition timing of the engine at idle. From Table C35, Figure 31 was drawn, showing the effect of timing with a load of 15 inches vacuum and an engine speed of 1500 rpm. Figure 32 shows horsepower effects under a load of 15 inches vacuum and engine speed of 4500 rpm. Figure 33 shows these effects for a load of 5 inches and a speed of 1500 rpm, and Figure 34 shows these effects for a load of 5 inches and a speed of 4500 rpm. Graphs were not shown for all engine conditions because the basic trends can be seen from a few graphs.

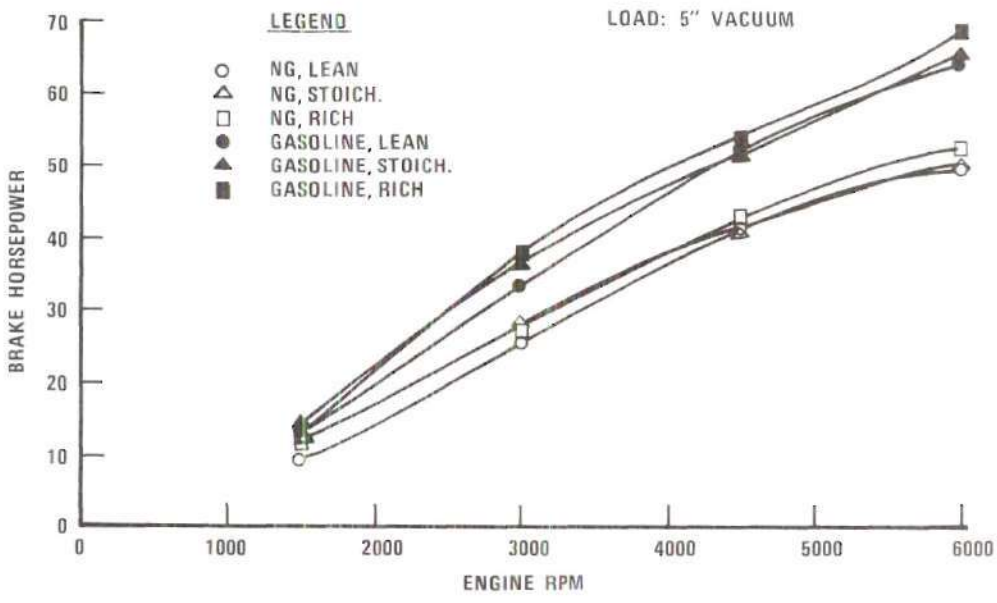


Figure 28. Wankel Horsepower Curve.

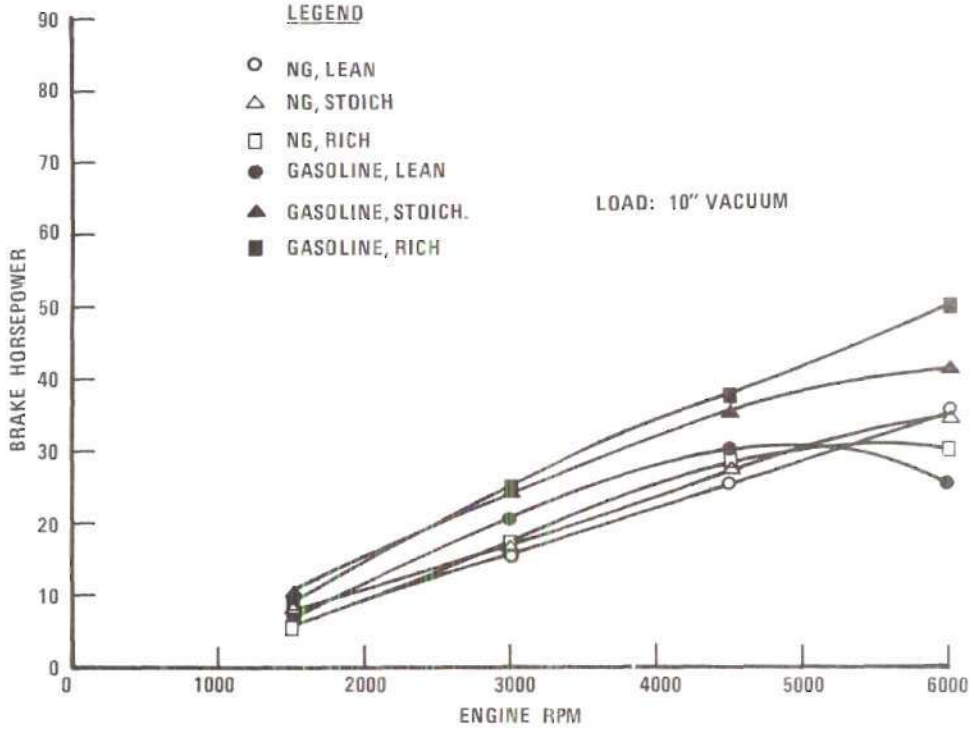


Figure 29. Wankel Horsepower Curve.

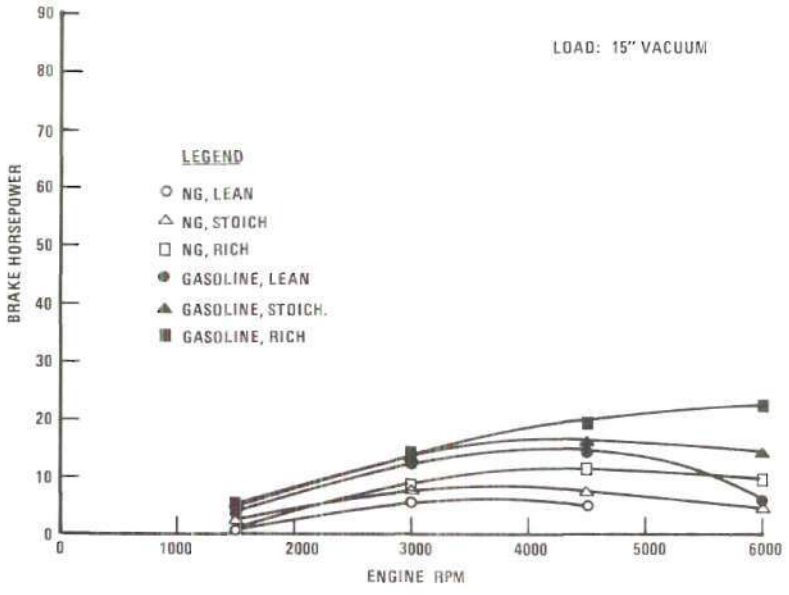


Figure 30. Wankel Horsepower Curve.

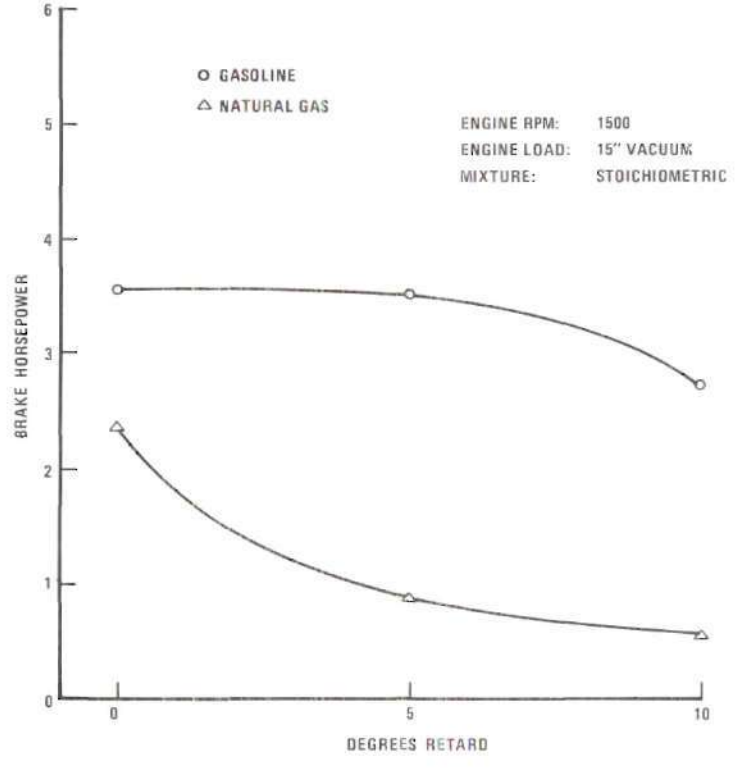


Figure 31. Horsepower Variation with Timing

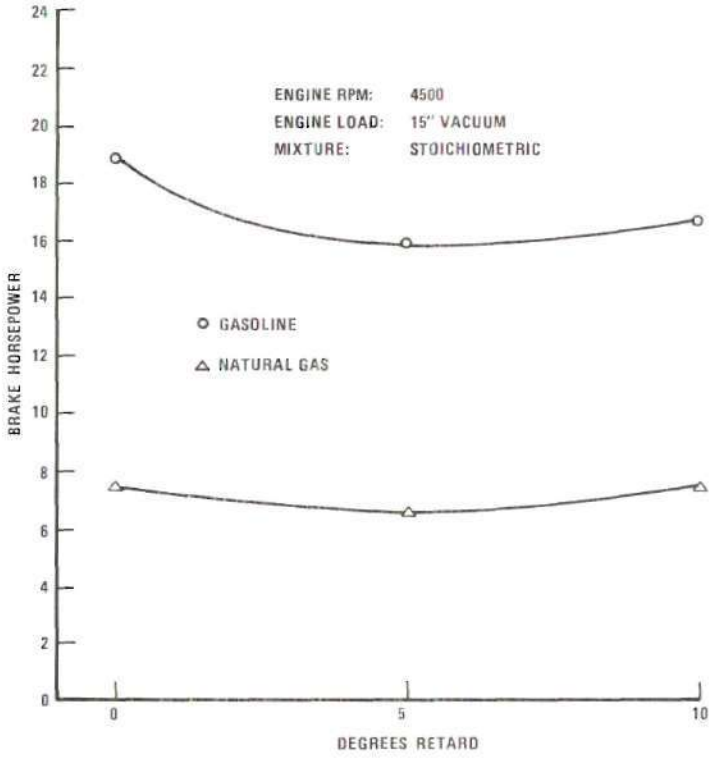


Figure 32. Horsepower Variation with Timing.

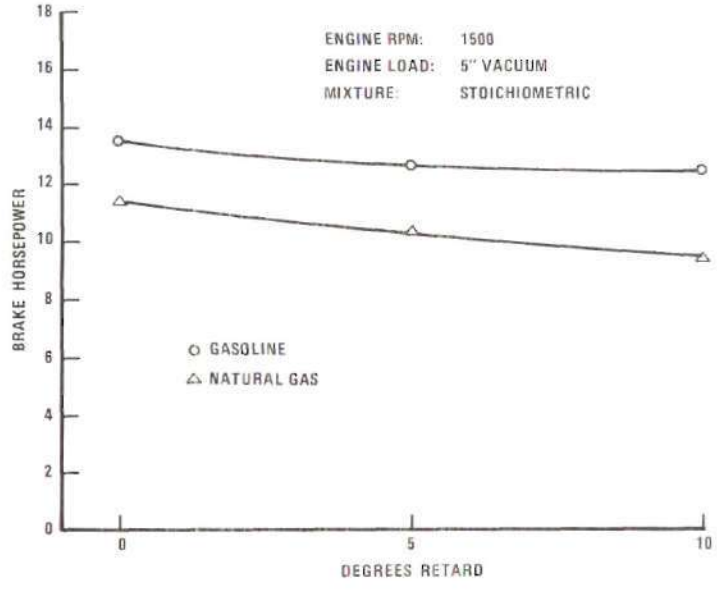


Figure 33. Horsepower Variation with Timing.

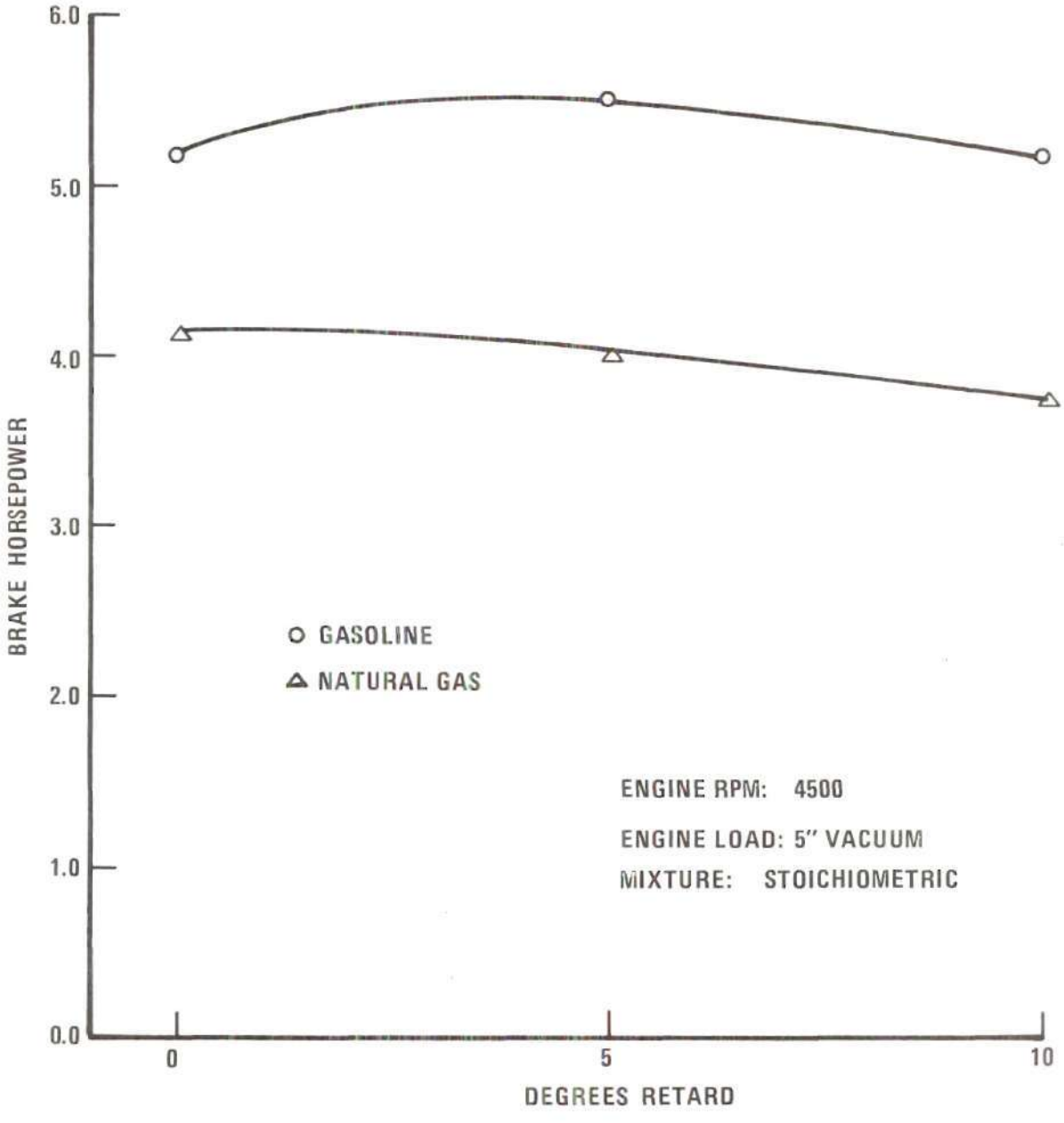


Figure 34. Horsepower Variation with Timing.

Discussion of Results

A. Emissions Variation with Engine Speed

Figures 11, 12, and 13 display essentially the same information for three different engine loads. In Figure 11 it can be seen that hydrocarbons decrease with increasing rpm. As can be seen from Table C1, in the case of natural gas this decrease may be credited partly to the leaning out of the fuel mixture. However, the trend is the same for both natural gas and gasoline, and this trend is due primarily to the time element involved in the engine cycle. As engine speed increases, there is less time for unburned fuel mixture to leak past the apex seals on the rotor into the exhausting chamber before being burned. Also, there is less time for quenching of the burning charge by the cooler engine walls, thus producing unburned hydrocarbons.

NO pollutant concentrations do not change appreciably through the rpm range for the light load condition, and as can be seen from the graph, NO emissions with natural gas are considerably less than with gasoline. The CO does not seem to be affected appreciably by rpm at light load either, and again the pollutant levels are considerably lower for natural gas than gasoline. In Table C1 and the other tables that follow, ratios have been calculated for each pollutant by dividing the concentrations produced with natural gas by the concentrations produced with gasoline. This gives a fraction which is generally less than one, reflecting the reduction in pollutants with natural gas. As shown in Table C1, the fractions for each pollutant are then added and the average is taken. Using this method the NO ratio gives 0.41, the HC ratio

gives 0.65 and the CO ratio gives 0.56. In effect this says that the use of natural gas as fuel under these conditions reduces NO emissions by 59 per cent, HC emissions by 35 per cent, and CO emissions by 44 per cent.

Figure 12 and Table C2 show similar information, this time with a load of ten inches vacuum. The NO curve for gasoline shows a peak at about 4000 rpm, and this would be expected since the engine produces maximum torque at that speed, and maximum NO emissions should result since cylinder pressure and temperature will be at their peaks. The NO curve for natural gas does not show as pronounced a peak, but does show lowering of the NO at higher rpms where the torque falls off rapidly. Hydrocarbons in Figure 12 show the same trend as in Figure 11, for the same reasons. The CO emissions appear to be rather erratic and do not correlate well between natural gas (where the CO climbs at higher rpm) and gasoline (where the CO falls off). In looking at the air-fuel ratios in Table C2, one would expect CO on natural gas to fall off, since the mixture is becoming leaner at high rpms. This sheds some doubt on the accuracy of the CO meter, and indeed so do some points which will be seen later. It was mentioned in the description of apparatus that the CO measuring equipment had the least accuracy, but hopefully the total relative comparison between CO levels on natural gas and gasoline will be valid. As shown in Table C2, NO is reduced by 55 per cent using natural gas, HC by 26 per cent, and CO by 63 per cent.

Figure 13 and Table C3 show more of the same as Figures 11 and 12, this time with a heavy load of five inches vacuum. In this case

the NO curve on natural gas shows more of a peak. The CO curves are again to be wondered at, especially the 6000 rpm value on natural gas. Table C3 shows the air-fuel ratio to be 19, and if anything it would be expected that this point would have the lowest value of CO, since the predominate influence on CO is air-fuel mixture. Hydrocarbons are slightly higher for two points on natural gas than on gasoline. This is the first of several instances where it can be seen that natural gas does not do a very good job of decreasing HC emissions. For Figure 13 the reduction in NO is 50 per cent, reduction in CO is 45 per cent, and the reduction of HC is only 13 per cent.

B. Emissions Variation with Engine Load

In Figure 14 the engine speed has been held constant and the load has been varied. The NO curves show that higher NO concentrations are produced at higher loads, and this is to be expected, since higher torques are being produced. The HC curves show a tendency for lower emissions under higher loads. This may be partially due to the fact that the air-fuel ratios leaned out slightly under heavier loads (see Table C4) but it is probably due more to higher combustion temperatures promoting more complete combustion. Again, the CO readings are rather erratic, especially the 10-inch load on gasoline. This point was rerun once and yielded almost exactly the same data so some doubt is cast on the other points. Again, these readings may have resulted from the poor accuracy of the CO instrument. As shown in Table C4, reductions in NO and CO using natural gas were substantial, but reduction of HC was only 9 per cent.

Figure 15 shows the same information as Figure 14, but this time the engine speed is 3000 rpm. It is interesting that the HC curves now have minimum points. Perhaps seal leakage becomes greater at higher loads for this rpm. It is also interesting that the CO curve for gasoline again has a peak at 10 inches load. It may be that this is a characteristic of the engine. Again, reductions in NO (55 per cent) and CO (61 per cent) are substantial, while HC reductions are only 27 per cent.

Figure 16 shows similar trends as the previous two figures, with slightly better relative reduction of HC emissions (38 per cent reduction).

Figure 17 is interesting in that the curves are closer together than previously. The five-inch load run (natural gas) was slightly lean, resulting in enough power drop to cause the NO curve to bend down at high load. Some lean misfire may have been occurring on natural gas resulting in the upswing of the HC curve. The CO levels on both fuels are very close at 6000 rpm. This probably indicates that the four-barrel carburetor mixes the air-fuel charge as well as the venturi mixer at high speeds. CO was only reduced by 6 per cent on natural gas.

C. Emission Variations with Ignition Timing

Figure 18 is the first of several graphs showing the effects of retarding the timing at idle. It is apparent that at 1500 rpm there is very little effect on emissions from small increments of spark retard. The low CO level (on gasoline) for the 10 degree retard is probably not accurate.

Figures 19, 20 and 21 all show the same fact: The effect on emissions of spark retard is slight, even under widely-varying conditions.

Figure 22 shows substantially the same information as the previous graphs, except for the large variation in CO on gasoline. This can be explained through the operation of the four-barrel carburetor. The retarded spark settings reduced power enough so that the vacuum-operated secondaries had to open up further to maintain the same operating point. Therefore, more raw fuel was dumped into the engine and CO levels went up. This can be seen from the air-fuel ratios for these runs in Table C19.

D. Emission Variations with Mixture

The data in Tables C20 through C31 shows some very interesting results. As mentioned before, only some of the tables were used to generate graphs, in the interest of time, considering the difficulty of controlling air-fuel ratio precisely. Also, no attempts was made to calculate emissions ratios for these curves since the points do not represent the same equivalence ratios for natural gas and gasoline.

Figure 23 is a medium load, low-speed condition, and again, the natural gas HC emissions are not too promising, surpassing the gasoline HC emissions near the stoichiometric air-fuel ratio for natural gas. This upward curve indicates lean misfire, which is not usually found at so low an air-fuel ratio in a conventional engine running on natural gas. As espected, CO emissions rise dramatically for both natural gas and gasoline at very rich mixtures. The NO curves both have peaks,

and these should coincide quite well with stoichiometric air-fuel ratios, which they do.

Figure 24 shows curves for the same low rpm as Figure 23, but this time under a heavy load. The NO peaks are more well defined, and the CO curves are similar to Figure 23. Again, the HC emissions are almost the same, but this time the lean misfire does not become as serious until higher air-fuel ratios.

Figure 25 shows a light load at 3000 rpm. Lean misfire is very bad in this case on natural gas, and there is some question of the validity of the lean HC point. CO levels are closer together for gasoline and natural gas than in previous curves.

Figure 26 presents the data for a medium load at 4500 rpm. Again, lean misfire on natural gas is pronounced, and CO and NO are considerably lower near normal operating conditions on natural gas.

Figure 27 shows a high load at 4500 rpm, and no lean misfire is evident, perhaps due to the fact that extremely lean data points were not available. NO curves show definite peaks, and again, CO and NO levels are lower on natural gas.

Thus it can be seen that two interesting facts about the Wankel engine are found from these curves. Lean misfire occurs to a higher degree at lighter loads, and this coincides with data taken from conventional engines. Lean misfire does not usually take a great upturn until an air-fuel ratio of about 21 on natural gas with a conventional engine is reached (19). However, as can be seen from the curves, the air-fuel ratio at which lean misfire becomes pronounced in the Wankel is about 18-20.

E. Horsepower Variation with Fuel

Figures 28, 29, and 30 clearly show the loss of horsepower due to the use of natural gas as a fuel. Variations in mixture are also shown on the curves, but these differences are not great in most instances. In Figure 28 a reduction in maximum power from about 67 horsepower to about 51 horsepower (or about 24 per cent) can be seen. Power reductions at lighter loads are less dramatic. It should be noted that lean misfire at 6000 rpm on gasoline drastically reduces power at low and medium loads.

F. Horsepower Variation with Ignition Timing

As can be seen from Figure 31, retardation of timing produces some loss of horsepower under light load and low rpm. Figure 32 shows very small changes in horsepower at 4500 rpm and 15 inches vacuum load. The apparent rises in horsepower at 10° retard probably results from richening of the air-fuel mixture. Figures 33 and 34 also show little effect of ignition timing on horsepower, although the trends seem to indicate slight loss of power with retarded spark.

CHAPTER V

CONCLUSIONS

The results given in Chapter IV enable several important conclusions to be drawn about the emissions characteristics of a Wankel engine. It has been shown that hydrocarbon emissions decrease significantly with an engine speed increase. Also, it can be seen that hydrocarbon emissions decrease as engine load increases. The effects have been noted in other works on both Wankel and conventional engines (19, 20).

Minimum hydrocarbon levels of the uncontrolled Wankel compare favorably to data available for a CFR engine at high load and low rpm. Both engines produce about 1000-1500 ppm on gasoline, at air-fuel ratios slightly leaner than stoichiometric (19).

Nitric oxide emissions were greatest under maximum torque engine conditions. Largest concentrations measured were in the neighborhood of 2000 ppm. This is a considerably lower NO level than was measured by one source with a CFR engine where measurements of high load, low rpm NO emissions approached 7000 ppm (19). Thus the probability of using a Wankel engine to solve NO emission problems looks promising.

Carbon monoxide emissions were affected greatly by air-fuel ratio, and this has also been found in other studies (19).

The overall effect of changing spark timing in the Wankel has been shown to be small, both in effects on exhaust emissions and horsepower.

It has been shown that the use of natural gas as the fuel for a Wankel engine will reduce the emissions of hydrocarbons, nitric oxide, and carbon monoxide to levels below those obtained with gasoline. Some further discussion is in order to determine the magnitude of these reductions.

First, consideration will be given to the data given in Tables C1 through C3, which reflect emissions variations with engine speed. In order to get an overall view of the emissions reduction, an average number has been compiled from the averages of these three tables. These averages give fractions of 0.45 for NO, 0.75 for HC, and 0.49 for CO, or reductions in NO of 55 per cent, reductions in HC of 25 per cent, and reductions in CO of 51 per cent.

Tables C4 through C7 show the emissions variations with engine load. Since these tables are rearrangements of the data used in Tables C1 through C3, the same overall averages will result.

Tables C8 through C19 present data for variations in ignition timing. The averages for these reduction fractions have been calculated as well and are as follows: 0.44 for NO, 0.86 for HC, and 0.41 for CO, or reductions in NO of 56 per cent, reduction in HC of 14 per cent, and reduction in CO of 59 per cent.

Fractions were not calculated for Tables C20 through C31 since corresponding mixture ratios for the two fuels were not presented.

Thus, the overall reduction in emission concentrations for the Wankel engine using natural gas is approximately 55 per cent of NO, 15-25 per cent of HC, and 50-60 per cent of CO. The use of natural gas

as a fuel to reduce emissions is therefore effective in reducing NO and CO, but not nearly so effective in the reduction of HC. It has been seen that the Wankel engine has been especially prone to lean misfire under light loads. This fact discourages the use of extremely lean mixtures for reduction of all pollutants.

As mentioned previously, the unburned hydrocarbons present in the exhaust gases of an engine burning natural gas are nearly 100 per cent methane, which is said to have nearly zero reactivity in photochemical smog reactions (12). If this fact is taken into account, a fractional multiplier may be used to reduce the HC emissions on natural gas. No provision is made for this in the Federal test procedures, however.

Therefore, it has been found in this research program that natural gas offers definite reductions of exhaust emissions when used in a Wankel engine. The reductions of CO and NO are substantial, but reduction of HC is not dramatic. Whether or not natural gas will see widespread use as an automotive fuel is an unanswered question, but its use could help reduce pollution in very congested areas and it might prove very attractive for fleet applications where refueling would not be such a problem.

As for the Wankel engine itself, extensive testing has shown it to be smooth, quiet, and efficient in terms of power developed per pound of engine weight. It will probably see widespread automotive applications in the future.

CHAPTER VI

RECOMMENDATIONS

Several problem areas developed in the laboratory that were not completely resolved at the time the testing for this paper was complete. Analysis of the data has shown that more accurate measurement of CO is needed. A new Olson-Horiba CO instrument is now on hand and will be installed in the sampling train for future tests. The cooling system for the Wankel engine still does not perform satisfactorily and needs to be replaced with a more efficient heat exchanger or radiator. Overall, however, the emissions laboratory carried out its designated functions quite well.

Now that the facility is in operation, further emissions tests need to be made. Since a Vega engine has been set up in the laboratory, a comparative study might be run between it and the Wankel engine from an emissions standpoint, and more information could be obtained to see if the Wankel is promising as a low-emission engine.

In addition, further work needs to be done on the Wankel. Experiments need to be carried out using gasoline and natural gas with the thermal reactor, so that its potential can be measured and emission levels can be further reduced. There are many other types of experiments which could be carried out in this laboratory, and hopefully it will be of use for some time to come.

APPENDIX A

SAMPLE CALCULATION OF AIR-FUEL RATIO

Natural Gas

The following raw data have been obtained:

Air flow manometer reading:	0.607 inches
Initial gas meter reading:	0 cubic feet
Final gas meter reading:	10 cubic feet
Time between meter readings:	2:42
Laboratory room temperature:	80°F
Barometric pressure:	29.45 inches Hg

Step 1

The calibration curve for the Meriam laminar flow element is entered for a pressure differential of 0.607 inches and the following is obtained:

Air Flow = 32.4 SCFM

Step 2

The above air flow is in standard cubic feet per minute (SCFM) and must be corrected for temperature and pressure variations. The flow element is calibrated at a temperature of 70°F and barametric pressure of 29.92 inches Hg. Correction tables are included in the instruction manual and the following values are given:

80°F gives a correction factor of 0.9674.
29.45 inches Hg gives a factor of 0.9843.

Therefore:

$$\text{Actual Flow (CFM)} = (32.4\ \text{SCFM})(0.9674)(0.9843)$$

$$\text{Actual Flow} = 30.8\ \text{CFM}$$

Step 3

The mass flow rate of air must be obtained next. This is done by multiplying the above by the air density. From the perfect gas law:

$$\rho_{air} = 0.0735\ \text{lbm/ft}^3$$

Therefore:

$$\dot{m}_A = \text{Mass Flow Rate of Air}$$

$$\dot{m}_A = (30.8)(\rho_{air})$$

$$= (30.8)(.0735)$$

$$= 2.26\ \text{lbm/min}$$

Step 4

The volume flow rate of natural gas is determined next.

$$\text{Total Volume} = 10 - 0 = 10 \text{ ft}^3$$

$$\text{Total Time} = 2{:}42 = 2.7 \text{ min.}$$

$$Q_{NG} = \frac{10 \text{ ft}^3}{2.7 \text{ min}} = 3.8 \text{ ft}^3/\text{min.}$$

This flow rate must be corrected for temperature, since the dry gas meter is calibrated at 60°F:

$$Q_{NG_{corrected}} = (3.8 \text{ ft}^3/\text{min})\left(\frac{540°R}{520°R}\right)$$

$$= 3.95 \text{ ft}^3/\text{min}$$

Step 5

The mass flow rate of natural gas must now be obtained. The density of natural gas at room temperature is also found from the perfect gas law:

$$\rho_{NG} = 0.0415 \text{ lbm/ft}^3$$

Therefore:

$\dot{m}_{NG}$ = Mass Flow Rate of Natural Gas

$= (Q_{NG_{corrected}})(\rho_{NO})$

$= (3.95\ ft^3/min)(0.0415\ lbm/ft^3)$

$= 0.164$ lbm/min

Step 6

Finally the air-fuel ratio can be found by dividing the mass flow rate of air by the mass flow rate of fuel:

$A/F = \dot{m}_A/\dot{m}_{NG}$

$= (2.26\ lbm/min)\ (0.164\ lbm/min)$

$A/F = 13.78$

Gasoline

The procedure for gasoline is simplified somewhat. Let us assume the following raw data have been obtained:

Air flow manometer reading:	0.607 inches
Initial gasoline weight:	3.00 lb.
Final gasoline weight:	2.22 lb.
Time between weight readings:	4.0 min.
Laboratory room temperature:	80°F
Barometric pressure:	29.45 inches Hg

Step 1

Note that the above will give the same air flow as for the natural gas case:

$$\dot{m}_A = 2.26 \text{ lbm/min}$$

Step 2

Gasoline mass flow rate can be easily determined:

$$\text{Gasoline Burned} = 3.00 - 2.22 = 0.78 \text{ lb.}$$

$$\dot{m}_G = \frac{0.7816}{4.0 \text{ min}} = 0.195 \text{ lbm/min}$$

Step 3

$$A/F = \dot{m}_A/\dot{m}_G$$

$$= (2.26 \text{ lbm/min})/0.195 \text{ lbm/min})$$

$$A/F = 11.60$$

APPENDIX B

CORRECTION FOR EXHAUST DILUTION

The *Federal Register* specifies calculations for corrections of exhaust gas concentration inaccuracies due to dilution. For gasoline, the following formula is used (9):

$$\text{C.F. (Correction Factor)} = \frac{14.5}{\%\ CO_2 + (0.5)\%CO + (6)\%HC}$$

An example will be shown using the following data:

CO_2 = 12.5%

CO = 0.31%

HC = 1131 ppm = 0.1131%

Therefore:

$$\text{C.F.} = \frac{14.5}{12.5 + (0.5)(0.31) + 6(0.1131)}$$

$$= 1.087$$

The numbers obtained for the pollutant concentrations must now be multiplied by this correction factor to obtain corrected values:

$$NO_{corr} = (1.087)(NO)$$

$$= (1.807)(1575) = 1713 \text{ ppm}$$

$$HC_{corr} = (1.087)(HC)$$

$$= (1.087)(1131) = 1230 \text{ ppm}$$

$$CO_{corr} = (1.087)(CO)$$

$$= (1.087)(0.31) = 0.34\%$$

Natural gas cannot be expected to provide 14.5% CO_2 at stoichiometric conditions. General practice dictates the substitution of 11 for 14.5 in the dilution correction formula (12).

Thus the correction formula for natural gas is:

$$C.F. = \frac{11.0}{\% CO_2 + (0.5)\%CO + (6)\%HC}$$

All data presented in this thesis have been corrected for dilution.

APPENDIX C

TABLES

Table C1. Emissions Variation with Engine Speed [Figure 13]

Engine Load: 15 inches vacuum
Mixture: Approximately stoichiometric
Timing: Factory specifications

Engine RPM	NATURAL GAS				GASOLINE				$\frac{NO_{NG}}{NO_{GAS}}$	$\frac{HC_{NG}}{HC_{GAS}}$	$\frac{CO_{NG}}{CO_{GAS}}$
	A/F	NO (ppm)	HC (ppm)	CO (%)	A/F	NO (ppm)	HC (ppm)	CO (%)			
1500	14.63	180	1477	0.18	15.20	447	1895	0.32	.40	.78	.56
3000	16.90	270	958	0.22	14.95	605	1577	0.34	.45	.61	.65
4500	18.00	235	907	0.17	15.40	749	1326	0.43	.31	.68	.40
6000	18.40	289	588	0.23	16.70	603	1104	0.36	.48	.53	.64
							AVG:		.41	.65	.56

Table C2. Emissions Variation with Engine Speed [Figure 14]

Engine Load: 10 inches vacuum
Mixture: Approximately stoichiometric
Timing: Factory specifications

Engine RPM	NATURAL GAS				GASOLINE				NO_{NG}/NO_{GAS}	HC_{NG}/HC_{GAS}	CO_{NG}/CO_{GAS}
	A/F	NO (ppm)	HC (ppm)	CO (%)	A/F	NO (ppm)	HC (ppm)	CO (%)			
1500	16.55	296	1366	0.06	15.82	774	1472	0.74	0.38	0.93	0.08
3000	17.70	512	675	0.09	15.72	1425	1052	0.46	0.36	0.64	0.20
4500	17.80	729	597	0.12	16.52	1464	865	0.42	0.50	0.69	0.29
6000	18.20	708	457	0.24	15.92	1236	656	0.26	0.57	0.70	0.92
							AVG:		0.45	0.74	0.37

Table C3. Emissions Variation with Engine Speed [Figure 15]

Engine Load: 5 inches vacuum
Mixture: Approximately stoichiometric
Timing: Factory specifications

Engine RPM	NATURAL GAS				GASOLINE				NO_{NG}/NO_{GAS}	HC_{NG}/HC_{GAS}	CO_{NG}/CO_{GAS}
	A/F	NO (ppm)	HC (ppm)	CO (%)	A/F	NO (ppm)	HC (ppm)	CO (%)			
1500	16.70	848	1259	0.04	16.65	1713	1230	0.34	0.50	1.02	0.12
3000	17.22	1091	1059	0.08	15.10	1967	1111	0.25	0.55	0.95	0.32
4500	17.32	1104	461	0.13	15.20	2004	908	0.25	0.55	0.51	0.52
6000	19.00	694	694	0.29	15.10	1698	690	0.23	0.41	1.00	1.26
							AVG:		0.50	0.87	0.55

Table C4. Emissions Variation with Engine Load
[Figure 16]

Engine RPM: 1500
Mixture: Approximately stoichiometric
Timing: Factory specifications

Engine Load (In. Vac.)	NATURAL GAS				GASOLINE				$\frac{NO_{NG}}{NO_{GAS}}$	$\frac{HC_{NG}}{HC_{GAS}}$	$\frac{CO_{NG}}{CO_{GAS}}$
	A/F	NO (ppm)	HC (ppm)	CO (%)	A/F	NO (ppm)	HC (ppm)	CO (%)			
5 (6 for Gas)	16.70	848	1259	0.04	16.65	1713	1230	0.34	0.50	1.02	0.12
10	16.55	296	1366	0.06	15.82	774	1472	0.74	0.38	0.93	0.08
15	14.63	180	1477	0.18	15.20	447	1895	0.32	0.40	0.78	0.56
							AVG:		0.43	0.91	0.25

Table C5. Emissions Variation with Engine Load
[Figure 17]

Engine RPM: 3000
Mixture: Approximately stoichiometric
Timing: Factory specifications

Engine Load (In. Vac.)	NATURAL GAS				GASOLINE				$\frac{NO_{NG}}{NO_{GAS}}$	$\frac{HC_{NG}}{HC_{GAS}}$	$\frac{CO_{NG}}{CO_{GAS}}$
	A/F	NO (ppm)	HC (ppm)	CO (%)	A/F	NO (ppm)	HC (ppm)	CO (%)			
5	17.22	1091	1059	0.08	15.10	1967	1111	0.25	0.55	0.95	0.32
10	17.70	512	675	0.09	15.72	1425	1052	0.46	0.36	0.64	0.20
15	16.90	270	958	0.22	14.95	605	1577	0.34	0.45	0.61	0.65
							AVG:		0.45	0.73	0.39

Table C6. Emissions Variation with Engine Load
[Figure 18]

Engine RPM: 4500
Mixture: Approximately stoichiometric
Timing: Factory specifications

Engine Load (In. Vac.)	NATURAL GAS				GASOLINE				$\frac{NO_{NG}}{NO_{GAS}}$	$\frac{HC_{NG}}{HC_{GAS}}$	$\frac{CO_{NG}}{CO_{GAS}}$
	A/F	NO (ppm)	HC (ppm)	CO (%)	A/F	NO (ppm)	HC (ppm)	CO (%)			
5	17.32	1104	461	0.13	15.20	2004	908	0.25	0.55	0.51	0.52
10	17.80	729	597	0.12	16.52	1464	865	0.42	0.50	0.69	0.29
15	18.00	235	907	0.17	15.40	749	1326	0.43	0.31	0.68	0.40
							AVG:		0.45	0.62	0.40

Table C7. Emissions Variation with Engine Load
[Figure 19]

Engine RPM: 6000
Mixture: Approximately stoichiometric
Timing: Factory specifications

Engine Load (In. Vac.)	NATURAL GAS				GASOLINE				$\frac{NO_{NG}}{NO_{GAS}}$	$\frac{HC_{NG}}{HC_{GAS}}$	$\frac{CO_{NG}}{CO_{GAS}}$
	A/F	NO (ppm)	HC (ppm)	CO (%)	A/F	NO (ppm)	HC (ppm)	CO (%)			
5	19.00	694	694	0.29	15.10	1698	690	0.23	0.41	1.00	1.26
10	18.70	708	457	0.24	15.92	1236	656	0.26	0.57	0.70	0.92
15	18.40	289	588	0.23	16.70	603	1104	0.36	0.48	0.53	0.64
							AVG:		0.49	0.74	0.94

Table C8. Emissions Variation with Ignition Timing

Engine RPM: 1500
Engine Load: 15 inches vacuum
Mixture: Approximately stoichiometric

Degrees Retard	NATURAL GAS A/F	NO (ppm)	HC (ppm)	CO (%)	GASOLINE A/F	NO (ppm)	HC (ppm)	CO (%)	$\frac{NO_{NG}}{NO_{GAS}}$	$\frac{HC_{NG}}{HC_{GAS}}$	$\frac{CO_{NG}}{CO_{GAS}}$
0	14.63	180	1477	0.18	15.20	447	1895	0.32	0.40	0.78	0.56
5	18.10	153	1745	0.16	13.60	466	1976	0.35	0.33	0.88	0.46
10	16.90	107	1520	0.17	15.45	451	1317	0.39	0.24	1.15	0.44
							AVG:		0.32	0.94	0.48

Table C9. Emissions Variation with Ignition Timing [Figure 20]

Engine RPM: 1500
Engine Load: 10 inches vacuum
Mixture: Approximately stoichiometric

Degrees Retard	NATURAL GAS A/F	NO (ppm)	HC (ppm)	CO (%)	GASOLINE A/F	NO (ppm)	HC (ppm)	CO (%)	$\frac{NO_{NG}}{NO_{GAS}}$	$\frac{HC_{NG}}{HC_{GAS}}$	$\frac{CO_{NG}}{CO_{GAS}}$
0	16.55	296	1366	0.06	15.82	774	1472	0.74	0.38	0.93	0.08
5	16.79	313	1204	0.13	14.39	887	1297	0.61	0.35	0.93	0.21
10	16.41	334	1141	0.10	15.65	791	1279	0.18	0.42	0.89	0.56
							AVG:		0.38	0.92	0.28

Table C10. Emissions Variation with Ignition Timing

Engine RPM: 1500
Engine Load: 5 inches vacuum
Mixture: Approximately stoichiometric

Degrees Retard	NATURAL GAS A/F	NO (ppm)	HC (ppm)	CO (%)	GASOLINE A/F	NO (ppm)	HC (ppm)	CO (%)	$\frac{NO_{NG}}{NO_{GAS}}$	$\frac{HC_{NG}}{HC_{GAS}}$	$\frac{CO_{NG}}{CO_{GAS}}$
0	16.70	848	1259	0.04	16.65	1713	1230	0.34	0.50	1.02	0.12
5	17.39	558	1274	0.11	14.15	1154	1578	0.26	0.48	0.81	0.42
10	16.54	498	1302	0.10	14.52	1076	1371	0.52	0.46	0.95	0.19
							AVG.		0.48	0.93	0.25

Table C11. Emissions Variation with Ignition Timing

Engine RPM: 3000
Engine Load: 15 inches vacuum
Mixture: Approximately stoichiometric

Degrees Retard	NATURAL GAS A/F	NO (ppm)	HC (ppm)	CO (%)	GASOLINE A/F	NO (ppm)	HC (ppm)	CO (%)	$\frac{NO_{NG}}{NO_{GAS}}$	$\frac{HC_{NG}}{HC_{GAS}}$	$\frac{CO_{NG}}{CO_{GAS}}$
0	16.90	270	958	0.22	14.95	605	1577	0.34	0.45	0.61	0.65
5	17.69	251	998	0.16	15.80	828	1182	0.28	0.30	0.84	0.57
10	17.17	279	850	0.15	16.70	687	1022	0.32	0.41	0.83	0.47
							AVG:		0.38	0.76	0.56

Table C12. Emissions Variation with Ignition Timing [Figure 21]

Engine RPM: 3000
Engine Load: 10 inches vacuum
Mixture: Approximately stoichiometric

	NATURAL GAS				GASOLINE						
Degrees Retard	A/F	NO (ppm)	HC (ppm)	CO (%)	A/F	NO (ppm)	HC (ppm)	CO (%)	$\frac{NO_{NG}}{NO_{GAS}}$	$\frac{HC_{NG}}{HC_{GAS}}$	$\frac{CO_{NG}}{CO_{GAS}}$
0	17.70	512	675	0.09	15.72	1425	1052	0.46	0.36	0.64	0.20
5	18.37	444	701	0.14	16.70	1024	915	0.46	0.43	0.77	0.30
10	17.81	437	654	0.12	15.70	1252	653	0.41	0.35	1.00	0.29
							AVG:		0.38	0.80	0.27

Table C13. Emissions Variation with Ignition Timing [Figure 22]

Engine RPM: 3000
Engine Load: 5 inches vacuum
Mixture: Approximately stoichiometric

	NATURAL GAS				GASOLINE						
Degrees Retard	A/F	NO (ppm)	HC (ppm)	CO (%)	A/F	NO (ppm)	HC (ppm)	CO (%)	$\frac{NO_{NG}}{NO_{GAS}}$	$\frac{HC_{NG}}{HC_{GAS}}$	$\frac{CO_{NG}}{CO_{GAS}}$
0	17.22	1091	1059	0.08	15.10	1967	1111	0.60	0.55	0.95	0.32
5	16.65	692	742	0.14	16.65	1654	1091	0.31	0.42	0.68	0.45
10	17.81	437	654	0.12	16.30	1606	899	0.30	0.27	0.73	0.40
							AVG:		0.41	0.79	0.39

Table C14. Emissions Variation with Ignition Timing

Engine RPM: 4500
Engine Load: 15 inches vacuum
Mixture: Approximately stoichiometric

Degrees Retard	NATURAL GAS				GASOLINE				$\frac{NO_{NG}}{NO_{GAS}}$	$\frac{HC_{NG}}{HC_{GAS}}$	$\frac{CO_{NG}}{CO_{GAS}}$
	A/F	NO (ppm)	HC (ppm)	CO (%)	A/F	NO (ppm)	HC (ppm)	CO (%)			
0	18.00	235	907	0.17	15.40	749	1326	0.43	0.31	0.68	0.40
5	18.26	225	1125	0.21	16.40	738	1479	0.40	0.30	0.76	0.53
10	18.36	255	907	0.19	15.36	753	1250	0.52	0.34	0.73	0.37
							AVG:		0.32	0.72	0.43

Table C15. Emissions Variation with Ignition Timing [Figure 23]

Engine RPM: 4500
Engine Load: 10 inches vacuum
Mixture: Approximately stoichiometric

Degrees Retard	NATURAL GAS				GASOLINE				$\frac{NO_{NG}}{NO_{GAS}}$	$\frac{HC_{NG}}{HC_{GAS}}$	$\frac{CO_{NG}}{CO_{GAS}}$
	A/F	NO (ppm)	HC (ppm)	CO (%)	A/F	NO (ppm)	HC (ppm)	CO (%)			
0	17.80	729	597	0.12	16.52	1464	865	0.42	0.50	0.69	0.29
5	18.19	575	619	0.19	15.90	1117	694	0.34	0.51	0.89	0.56
10	17.95	524	542	0.19	14.95	1023	886	0.30	0.51	0.61	0.63
							AVG:		0.51	0.73	0.49

Table C16. Emissions Variation with Ignition Timing

Engine RPM: 4500
Engine Load: 5 inches vacuum
Mixture: Approximately stoichiometric

Degrees Retard	NATURAL GAS				GASOLINE				$\frac{NO_{NG}}{NO_{GAS}}$	$\frac{HC_{NG}}{HC_{GAS}}$	$\frac{CO_{NG}}{CO_{GAS}}$
	A/F	NO (ppm)	HC (ppm)	CO (%)	A/F	NO (ppm)	HC (ppm)	CO (%)			
0	17.32	1104	461	0.13	15.20	2004	908	0.25	0.55	0.51	0.52
5	17.00	986	426	0.18	13.50	1238	866	0.62	0.80	0.49	0.29
10	17.95	524	542	0.19	14.64	1313	802	0.95	0.40	0.68	0.20
								AVG:	0.58	0.56	0.34

Table C17. Emissions Variation with Ignition Timing

Engine RPM: 6000
Engine Load: 15 inches vacuum
Mixture: Approximately stoichiometric

Degrees Retard	NATURAL GAS				GASOLINE				$\frac{NO_{NG}}{NO_{GAS}}$	$\frac{HC_{NG}}{HC_{GAS}}$	$\frac{CO_{NG}}{CO_{GAS}}$
	A/F	NO (ppm)	HC (ppm)	CO (%)	A/F	NO (ppm)	HC (ppm)	CO (%)			
0	17.50	270	1232	0.20	16.70	603	1104	0.36	0.45	1.12	0.56
5	18.79	308	2797	0.22	16.20	496	1675	0.33	0.62	1.67	0.67
10	-	-	-	-	15.64	549	984	0.37	-	-	-
								AVG:	0.53	1.39	0.61

Table C18. Emissions Variation with Ignition Timing

Engine RPM: 6000
Engine Load: 10 inches vacuum
Mixture: Approximately stoichiometric

Degrees Retard	NATURAL GAS A/F	NATURAL GAS NO (ppm)	NATURAL GAS HC (ppm)	NATURAL GAS CO (%)	GASOLINE A/F	GASOLINE NO (ppm)	GASOLINE HC (ppm)	GASOLINE CO (%)	$\frac{NO_{NG}}{NO_{GAS}}$	$\frac{HC_{NG}}{HC_{GAS}}$	$\frac{CO_{NG}}{CO_{GAS}}$
0	16.98	686	968	0.15	15.92	1236	656	0.24	0.56	1.48	0.63
5	16.97	487	369	0.22	14.82	1003	616	0.38	0.49	0.60	0.58
10	16.50	417	362	0.19	16.61	854	558	0.06	0.49	0.65	3.17
							AVG:		0.51	0.91	1.46

Table C19. Emissions Variation with Ignition Timing [Figure 24]

Engine RPM: 6000
Engine Load: 5 inches vacuum
Mixture: Approximately stoichiometric

Degrees Retard	NATURAL GAS A/F	NATURAL GAS NO (ppm)	NATURAL GAS HC (ppm)	NATURAL GAS CO (%)	GASOLINE A/F	GASOLINE NO (ppm)	GASOLINE HC (ppm)	GASOLINE CO (%)	$\frac{NO_{NG}}{NO_{GAS}}$	$\frac{HC_{NG}}{HC_{GAS}}$	$\frac{CO_{NG}}{CO_{GAS}}$
0	19.00	694	694	0.29	15.10	1698	690	0.23	0.41	1.00	1.26
5	16.97	751	566	0.32	13.60	1160	1119	1.20			
10	16.88	643	596	0.28	13.30	1161	988	1.12			

Table C20. Emissions Variation with Air-Fuel Mixture

Engine RPM: 1500
Engine Load: 15 inches vacuum
Timing: Factory specifications

NATURAL GAS				GASOLINE			
A/F	NO (ppm)	HC (ppm)	CO (%)	A/F	NO (ppm)	HC (ppm)	CO (%)
17.30	117	2122	0.22	16.90	648	1572	0.32
14.63	180	1477	0.18	15.20	447	1895	0.32
14.05	211	2958	0.23	12.95	353	2964	1.68

Table C21. Emissions Variation with Air-Fuel Mixture [Figure 25]

Engine RPM: 1500
Engine Load: 10 inches vacuum
Timing: Factory specifications

NATURAL GAS				GASOLINE			
A/F	NO (ppm)	HC (ppm)	CO (%)	A/F	NO (ppm)	HC (ppm)	CO (%)
18.70	174	2497	0.12	19.9	564	1845	0.20
16.55	296	1366	0.06	15.82	774	1472	0.74
12.85	171	1978	1.36	17.40	607	2342	1.49

Table C22. Emissions Variation with Air-Fuel Mixture [Figure 26]

Engine RPM: 1500
Engine Load: 5 inches vacuum
Timing: Factory specifications

NATURAL GAS				GASOLINE			
A/F	NO (ppm)	HC (ppm)	CO (%)	A/F	NO (ppm)	HC (ppm)	CO (%)
21.40	188	2168	0.08	18.60	1612	1634	0.17
16.70	848	1259	0.04	16.65	1713	1230	0.34
12.92	258	2036	1.57	13.20	676	2624	1.52

Table C23. Emissions Variation with Air-Fuel Mixture [Figure 27]

Engine RPM: 3000
Engine Load: 15 inches vacuum
Timing: Factory specifications

NATURAL GAS				GASOLINE			
A/F	NO (ppm)	HC (ppm)	CO (%)	A/F	NO (ppm)	HC (ppm)	CO (%)
14.20	219	1127	1.30	18.60	765	1234	0.21
16.90	270	958	0.22	14.95	605	1577	0.34
20.50	184	3531	0.11	13.10	464	2344	1.68

Table C24. Emissions Variation with Air-Fuel Mixture

Engine RPM: 3000
Engine Load: 10 inches vacuum
Timing: Factory Specifications

NATURAL GAS				GASOLINE			
A/F	NO (ppm)	HC (ppm)	CO (%)	A/F	NO (ppm)	HC (ppm)	CO (%)
18.28	340	810	0.13	20.5	1105	1361	0.25
17.70	512	675	0.09	15.72	1425	1052	0.46
16.94	750	742	0.07	12.98	941	1688	1.25

Table C25. Emissions Variation with Air-Fuel Mixture

Engine RPM: 3000
Engine Load: 5 inches vacuum
Timing: Factory specifications

NATURAL GAS				GASOLINE			
A/F	NO (ppm)	HC (ppm)	CO (%)	A/F	NO (ppm)	HC (ppm)	CO (%)
18.15	642	794	0.14	17.7	1810	1267	0.22
17.22	1099	1059	0.08	15.10	1967	1111	0.60
16.90	928	708	0.09	13.05	801	2013	1.67

Table C26. Emissions Variation with Air-Fuel Mixture

Engine RPM: 4500
Engine Load: 15 inches vacuum
Timing: Factory specifications

NATURAL GAS				GASOLINE			
A/F	NO (ppm)	HC (ppm)	CO (%)	A/F	NO (ppm)	HC (ppm)	CO (%)
18.55	169	2405	0.24	18.70	715	998	0.33
18.00	235	907	0.17	15.40	749	1326	0.51
17.48	367	881	0.17	13.10	791	795	0.91

Table C27. Emissions Variation with Air-Fuel Mixture

Engine RPM: 4500
Engine Load: 10 inches vacuum
Timing: Factory specifications

NATURAL GAS				GASOLINE			
A/F	NO (ppm)	HC (ppm)	CO (%)	A/F	NO (ppm)	HC (ppm)	CO (%)
21.30	207	1669	0.10	20.10	1252	1030	0.31
17.80	729	597	0.12	16.52	1464	865	0.42
13.90	289	1099	1.91	13.05	938	1555	1.45

Table C28. Emissions Variation with Air-Fuel Mixture [Figure 29]

Engine RPM: 4500
Engine Load: 5 inches vacuum
Timing: Factory specifications

NATURAL GAS				GASOLINE			
A/F	NO (ppm)	HC (ppm)	CO (%)	A/F	NO (ppm)	HC (ppm)	CO (%)
18.60	777	419	0.12	18.0	1844	795	0.59
17.32	1104	461	0.13	15.20	2004	908	0.25
15.85	1066	450	0.15	13.70	1146	1628	1.98
14.35	600	712	1.33	-	-	-	-

Table C29. Emissions Variation with Air-Fuel Mixture

Engine RPM: 6000
Engine Load: 15 inches vacuum
Timing: Factory specifications

NATURAL GAS				GASOLINE			
A/F	NO (ppm)	HC (ppm)	CO (%)	A/F	NO (ppm)	HC (ppm)	CO (%)
-	-	-	-	19.00	449	2477	0.40
17.50	270	1232	0.20	16.70	603	1104	0.36
16.84	306	639	0.21	13.50	806	703	0.66

Table C30. Emissions Variation with Air-Fuel Mixture

Engine RPM: 6000
Engine Load: 10 inches vacuum
Timing: Factory specifications

NATURAL GAS				GASOLINE			
A/F	NO (ppm)	HC (ppm)	CO (%)	A/F	NO (ppm)	HC (ppm)	CO (%)
17.68	622	414	0.25	18.20	716	1617	0.35
16.98	686	968	0.15	15.92	1236	656	0.24
16.25	467	428	0.16	13.42	1207	1568	1.32

Table C31. Emissions Variation with Air-Fuel Mixture

Engine RPM: 6000
Engine Load: 5 inches vacuum
Timing: Factory specifications

NATURAL GAS				GASOLINE			
A/F	NO (ppm)	HC (ppm)	CO (%)	A/F	NO (ppm)	HC (ppm)	CO (%)
17.45	908	519	0.19	19.90	1630	560	0.42
16.96	817	1181	0.22	15.10	1698	690	0.23
16.45	779	570	0.35	13.30	1256	1468	0.58

Table C32. Horsepower Curves [Figure 30]

Vacuum = 5 inches

		NG Lean		NG Stoich.		NG Rich		Gas Lean		Gas Stoich.		Gas Rich	
	RPM	Torque	HP	Torque	HP	Torque	HP	Torque	HP	Torque	HP	Torque	HP
.25	1500	38.3	9.6	45.5	11.4	46.3	11.6	50.0	12.5	54.3	13.6	50.0	12.5
.50	3000	50.7	25.4	56.1	28.1	54.8	27.4	66.3	33.2	72.5	36.3	74.4	37.2
.75	4500	55.5	41.6	55.1	41.4	56.0	42.0	69.8	52.3	69.3	51.9	71.8	53.9
1.0	6000	49.7	49.7	49.7	49.7	52.5	52.5	64.1	64.1	65.9	65.4	68.4	68.4

Table C33. Horsepower Curves [Figure 31]

Vacuum = 10 inches

		NATURAL GAS						GASOLINE					
		Lean		Stoich.		Rich		Lean		Stoich.		Rich	
	RPM	Torque	HP	Torque	HP	Torque	HP	Torque	HP	Torque	HP	Torque	HP
.25	1500	23.1	5.8	28.2	7.1	26.6	6.7	28.5	7.1	40.9	10.2	37.4	9.4
.50	3000	31.8	15.9	33.3	16.7	35.3	17.7	41.0	20.5	48.9	24.4	49.6	24.8
.75	4500	33.9	25.5	36.6	27.4	38.3	28.7	40.0	30.0	47.5	35.6	50.4	37.8
1.00	6000	35.4	35.4	34.3	34.3	30.0	30.0	25.6	25.6	41.9	41.9	50.8	50.8

Table C34. Horsepower Curves [Figure 32]

Vacuum = 15 inches

		NATURAL GAS						GASOLINE					
		Lean		Stoich.		Rich		Lean		Stoich.		Rich	
	RPM	Torque	HP	Torque	HP	Torque	HP	Torque	HP	Torque	HP	Torque	HP
.25	1500	2.5	.06	9.5	2.4	3.1	0.8	15.0	3.7	18.2	4.5	16.8	4.2
.50	3000	11.7	5.9	14.7	7.4	16.8	8.4	24.4	12.2	25.3	12.7	27.1	13.16
.75	4500	6.6	5.0	10.0	7.5	15.2	11.4	19.4	14.6	21.9	16.5	26.4	19.8
1.00	6000	-	-	4.9	4.9	9.6	9.6	5.4	5.4	14.2	14.2	22.3	22.3

Table C35. Horsepower Variations with Timing [Figure 33]

Engine RPM: 1500
Engine Load: 15 inches vacuum
Mixture: Stoichiometric

Degrees Retard	NATURAL GAS		GASOLINE	
	Torque	HP	Torque	HP
0	9.5	2.38	14.2	3.55
5	3.5	0.88	14.0	3.50
10	2.3	0.58	10.9	2.73

Table C36. Horsepower Variations with Timing [Figure 34]

Engine RPM: 4500
Engine Load: 15 inches vacuum
Mixture: Stoichiometric

Degrees Retard	NATURAL GAS		GASOLINE	
	Torque	HP	Torque	HP
0	10.0	7.50	25.3	18.98
5	8.9	6.68	21.3	15.98
10	10.0	7.50	22.3	16.73

Table C37. Horsepower Variations with Timing [Figure 35]

Engine RPM: 1500
Engine Load: 5 inches vacuum
Mixture: Stoichiometric

Degrees Retard	NATURAL GAS		GASOLINE	
	Torque	HP	Torque	HP
0	45.5	11.38	54.3	13.56
5	41.3	10.33	50.4	12.60
10	37.8	9.45	49.9	12.48

Table C38. Horsepower Variations with Timing [Figure 36]

Engine RPM: 4500
Engine Load: 5 inches vacuum
Mixture: Stoichiometric

Degrees Retard	NATURAL GAS		GASOLINE	
	Torque	HP	Torque	HP
0	55.1	41.33	69.3	51.98
5	53.4	40.05	73.4	55.05
10	50.0	37.50	69.0	51.75

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